BRL

REPORT NO. 1136
JULY 1961

FINAL TECHNICAL SUMMARY REPORT

Period 20 June 1958 - 30 June 1961

BRL-ARPA DOPLOC SATELLITE DETECTION COMPLEX

ARPA Satellite Fence Series

A. H. Hodge

Report No. 25 in the Series

Department of the Army Project No. 503-06-011
Ordnance Management Structure Code No. 5210.11.143
BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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Shepherd Program, ARPA ORDER 8-58

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AHHodge/lp
Aberdeen Proving Ground, Md.
July 1961

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ABSTRACT

This report consists of a technical summary of the research and development program sponsored under ARPA Order 8-58 which led to the proposal of a system for detecting and tracking non-radiating orbiting satellites. An interim research facility consisting of an illuminating transmitter and two receiving stations with fixed antenna arrays was first established to determine the feasibility of using the Doppler principle coupled with extremely narrow bandwidth phase-locked tracking filters as a sensor system. The interim system established the feasibility of using the Doppler method and resulted in real data for which computational methods were developed which produced orbital parameters from single pass data over a single station. To meet the expected space population problem of detection and identification and to obtain a maximum range with practical emitted power, a scanned fan beam system was proposed in which a transmitter and a receiver antenna separated by about 1,000 miles would be synchronously scanned about the earth chord joining the two stations to sweep a half cylinder of

space volume 1,000 miles long and having a radius of 3,000 miles. An early order stopping further development work on the project prevented field testing of the proposed scanning system in a scale model. The engineering study indicates that the proposed DOPLOC system or slight modifications thereof may offer some unique advantages over other systems for surveillance type of detection, tracking, identification and cataloging of both active and non-radiating satellites.

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I. INTRODUCTION

Early in 1958 the Advanced Research Projects Agency (ARPA) took over the responsibility for and direction of a committee established by the Director of Guided Missiles for the purpose of investigating the technical problems involved in a national satellite tracking network. The committee, chaired by Captain K. M. Gentry, USN, established working groups in the areas of detection and tracking, communications, data processing, United States programs and foreign programs. An ad hoc committee, comprised of the chairmen of the five working groups, was formed when ARPA requested that immediate attention and emphasis be directed toward solution of the problem of detecting non-radiating or "dark" satellites.

Following a number of meetings of the working groups, the ad hoc committee, and the Gentry committee, a proposal for an interim solution to the dark satellite problem was prepared and presented to ARPA in a briefing by the Gentry committee. The committee proposed the use of satellite tracking techniques developed by the Naval Research Laboratory (Minitrack) and the Army Ordnance Ballistic Research Laboratories (DOPLOC), each modified to permit operation in the passive (non-radiating satellite) mode.

It was tentatively established that a national passive detection network should be able to detect objects having effective radar reflection cross sections of 0.1 square meter or greater at altitudes betwee 100 and 2,000 miles. It was further deemed desirable to be able to determine the orbit parameters, in a relatively short time and preferably within one orbit period, and to establish immediately that the object detected was in fact a new object or to identify it as a previously detected and known satellite.

The briefing to ARPA indicated that the state-of-the-art in the tracking field would not result in a system capable of fully meeting the desired characteristics. Specifically, it was pointed out that the technical limitations would reduce system capability to tracking a one square meter target to 1,000 miles altitude or less. The effects of meteors, aircraft, etc., on the tracking systems could not be completely predicted. Computational programs for orbit determination had not been developed. It was estimated that a fence spanning the United States in East-West

direction at about Latitude 32° and composed of two Minitrack and one DOPLOC complex could be installed and placed in initial operation within six months.

On 20 June 1958 the ARPA issued Order 8-58 to the Ballistic Research Laboratories. The order stated in part:

> "Pursuant to the provisions of DOD Directive dated 7 February 1958, the Secretary of Defense has approved and you are requested to proceed at once on behalf of ARPA to establish a Doppler system complex. This system is to be in accordance with BRL letter to ARPA of 8 May 1958, and will, in cooperation with the Minitrack satellite tracking system produce the capability of detecting, identifying, and orbit predicting of non-radiating objects in space."

Using state-of-the-art techniques and essentially available equipment BRL, with some help from the Signal Corps, USASEA, proceeded with a crash program and within six months, by 20 December 1958 had installed a three-station complex consisting of a 50-KW illuminator radio transmitter at Fort Sill, Oklahoma, and receiving stations at Forrest City, Arkansas and White Sands Missile Range, New Mexico. Three Minitrack type antennas were used at each station. Detection was by reflected signal from the transmitter via the satellite. The axes of the beams of the receiving and transmitting antennas were oriented to intersect in space at a distance of 900 miles from the stations. Of the three antennas at each station, one was directed vertically above the great circle joining the stations, one was directed 20 degrees above the horizon to the north and the other 20 degrees above the horizon to the south. In this manner the 76 x 8 degree fan-shaped beams were designed to detect the approach of a satellite as it came over the horizon, intercept it again overhead, and again as it receded toward the horizon. This system was placed in operation in January 1959.

BRL personnel, realizing from the beginning of the program that the interim system would have limited range and coverage, urged ARPA to supply funds and to authorize a research program designed to develop a realistic specification for a system capable of adequately meeting all of the original performance specifications. Amendment No. 3 to ARPA order 8-58 provided funds to extend the system and to undertake an extensive research program, investigating the problem areas which were responsible for the limited performance of the interim system. Other amendments established reporting procedures and provided funding. BRL was later relieved of the responsibility of routine tracking for the purpose of supplying data to the filter center.

An extensive engineering study of the system requirements was initiated by BRL, and tentative conclusions were outlined to ARPA representatives at a meeting at BRL on 14 April 1959 as briefly described in BRL Technical Note No. 1266, "An Approach to the Doppler Dark Satellite Detection Problem", by L. G. deBey, July 1959. The idea of using several pairs of scanned, co-plannar, fan-shaped beams to cover the volume above the United States was presented to ARPA in the Second Semi-Annual Summary Report for the Period 1 January to 30 July 1959, BRL Memorandum Report No. 1220, by L. G. deBey, V. W. Richard and R. B. Patton, under section V, entitled, "A New System Concept". By letter dated 19 November 1959, subject "Second Generation DOPLOC R & D Program" BRL submitted to ARPA a proposal covering a program of research and development work designed to validate the conclusions stated in BRL Memorandum Report No. 1220, and to test the performance of the proposed scanning beam DOPLOC system through the installation and operation of a scaled-down model.

This proposal was not approved. On 13 April 1960 Amendment No. 5 to ARPA order 8-58 was received. It stated "As a result of technical evaluations of the SHEPHERD Program, it has been determined that the DOPLOC system will not meet the immediate objectives of the satellite detection and tracking program assigned to the Advanced Research Projects Agency. Accordingly, further research on the DOPLOC system is not

required". The order further requested that plans for closing out the project be submitted to ARPA. The cessation of work came just after DOPLOC had demonstrated its ability to detect, track and compute reliable orbits within minutes after a single passage of a non-radiating satellite over a single station. It had the highest resolution or discrimination against meteors and other extraneous signal sources of any known electronic system of satellite detection. With the scanned fan shape beam type system proposed to ARPA, acquisition would be automatic and a minimum number of low cost stations would insure a sneak-proof coverage. Multiple target capability would be adequate for any forseeable density of satellites. The range and sensitivity of detection would be equivalent to or better than those of any other known system. The cost of providing volumetric coverage of the space above the United States to any given altitude would be less than, or at most equivalent to, the cost of a line type fence having coverage to the same altitude. Computing time required to produce an orbit ranged from five to 25 minutes on a slow computer of the ORDVAC type. With a modern high speed computer these times could be reduced to one tenth to one hundredth of the above values. The problem of data digitization and transmission in real time had been solved. The system would have a limited applicability to anti-satellite and ICBM defense.

II. EVOLUTION OF DOPLOC PASSIVE SATELLITE TRACKING SYSTEM

A. The Basic DOPLOC System

1. DOPLOC Derivation. The DOPLOC (DOPpler phase LOCk) system is a satellite tracking system using the phase-locked Doppler frequency tracking filter technique. Historically it evolved from DOVAP and PARDOP Doppler tracking systems developed by the Ballistic Research Laboratories. DOVAP (DOppler Velocity And Position) is an "active" Doppler tracking system, i.e., one which uses a transponder in the missile to return the signal to ground. PARDOP* (PAssive Ranging DOPpler) is a reflection Doppler tracking system. DOVAP and PARDOP utilize the Doppler principle for the accurate determination of missile trajectories and other flight phenomena. As originally conceived, DOPLOC was to be used in conjunction with an upper atmosphere ionosphere experiment to provide a high quality Doppler frequency record from a satellite carrying an ultra-stable frequency, low power radio transmitter. Single station, single pass operation was envisioned as a desirable goal and served as a basis for design and choice of system parameters. DOPLOC is a reflection Doppler tracking system consisting of one or more satellite illuminating radio transmitters and one or more Doppler frequency receiving radio receivers. By utilizing extremely narrow band filters in the receiving system it is possible to operate with the extremely low signal levels that are reflected from the satellites. By using proper station geometry it is possible to compute orbits of the satellites from single passes over a single pair of stations, i.e. transmitter and receiver.

2. Tracking Filters. The Doppler frequency phase-locked tracking filter is the heart of the DOPLOC system, providing a greatly improved signal-to-noise ratio of the output data and therefore increased range. The system is designed to take full advantage of the narrow bandwidth in signal-to-noise improvement. Predetection filtering performance is realized, taking full advantage of product detection preceded by linear amplifiers. The tracking filter is a phase-locked, audio frequency, electronic bandpass filter that continually follows or tracks the Doppler

* Developed for the Ballistic Research Laboratories by the Ralph M. Parsons Company, Pasadena, California, under contract no. DA-04-495-ORD-483.

frequency automatically. Its function in the DOPLOC receiving station is to make possible the detection and accurate frequency measurement of signals which are much weaker than the noise at the output of the receiver. Tracking of the Doppler frequency is accomplished automatically by means of a tight, phase-locked feed back loop, thereby enabling the use of an extremely narrow filter bandwidth to obtain a large signal-to-noise improvement. A unique feature of the Ballistic Research Laboratories' Interstate* tracking filter is the successful employment of a third order servo control circuit. This circuit gives the filter an effective memory and "aided tracking" type of operation which maintains good lock-on to the signal under widely varying dynamic flight conditions. Thus the narrowest possible bandwidth consistent with the radial acceleration component of motion can be used in order to achieve a maximum signal-to-noise improvement.

Bandwidths manually adjustable from 1.0 to 50 cps are available in the present models. The narrowest bandwidth gives the DOPLOC receiving station a capability of detecting and maintaining lock-on to a signal which is 38 db below the noise at the receiver output, i.e. the noise power within the receiver output bandwidth is 6300 times greater than the signal power. This is possible with the 1-cps filter bandwidth and 16 kc receiver bandwidth. A 16 kc bandwidth is used in order to pass a Doppler frequency shift of 12 dc and leave a 2 kc safety margin at each edge of the passband.

3. Sensitivity. The DOPLOC receiver system used vacuum tube preamplifiers with a noise figure (NF) of 2 to 3 db at 108 mc. The internal phase noise in the receiver local oscillators was low enough to permit operation down to 1 cps bandwidth (B). The tracking filter requires a minimum of 4 db output signal-to-noise ratio (S/N) to maintain lock-on. Based on these parameters the overall received power sensitivity (P_r) is computed as follows:

$$\begin{aligned} P_r &= NF \times KT \times B \times S/N \\ &= 2 \times 4 \times 10^{-21} \times 2.5 \\ &= 2 \times 10^{-20} \text{ watts} \end{aligned}$$

where K is Baltzmann's constant, and T is temperature.

* This tracking filter was designed for BRL by the Interstate Engineering Corporation, Anaheim, California, on contract DA-04-495-ORD-822.

With a steady, unmodulated signal of 2×10^{-20} watts into the receiver, the signal-to-noise ratio of the output of the tracking filter corresponds to an output phase jitter of 36° rms or 0.1 cycle. A signal about 3 db stronger is required to lock on initially with the automatic system. When signal frequency and amplitude dynamics require a larger bandwidth, the threshold received power level to maintain lock-on increases linearly with the bandwidth used. The exact bandwidth required to maintain lock-on is a function of the received signal strength, the rate-of-change of frequency and the type of modulation that may be deliberately or indirectly imposed on the signal. Ballistic Research Laboratories Memorandum Report No. 1173, "DOPLOC Tracking Filter" by Victor W. Richard, contains a discussion of the bandwidth selection problem and gives the basic equations and graphs of the relation between bandwidth, rate-of-change of frequency and signal-to-noise ratio.

4. Antennas. With the extreme sensitivities realized by the optimum use of very narrow bandwidths and the low noise receivers it is generally possible for tracking active satellites to use antennas that have sufficiently broad radiation patterns, that the antennas need be oriented only in the general direction of arrival of the expected signal. The direction in which the antennas are pointed need not be known accurately. Accurately known and controlled radiation phase patterns are not necessary. The only requirement on the antennas is that they deliver sufficient signal, preferably as nearly constant as possible, irrespective of the state of polarization of the incoming signal. As further discussion will show, the success of the passive DOPLOC system is dependent upon the most effective utilization of the best antennas known to the state-of-the-art. In addition to the three Minitrack type receiving antennas available at each receiving station, flat top, corner reflector and dipole antennas were also available.

5. Data Output. The basic data output of the receiving station is Doppler frequency correlated with time. Since very stable beat frequency sources can be used, the Doppler frequency record can be interpreted to

be a very accurate record of received carrier frequency. The Doppler frequency output of the tracking filter is sufficiently clean, if the filter is locked on at all, to permit direct electronic counting and read-out or print-out in any desired form such as arabic numerals, punched tape in binary code, IBM cards, wide paper analog frequency, magnetic tape, etc. These data can be used with appropriate computational programs to obtain the orbital parameters desired. The accuracy of the solution is determined largely by station geometry with respect to the satellite orbit and not by electronic equipment limitations and errors. Propagation effects must be taken into account for maximum accuracy. When locked, the tracking filter output is within 90° or 1/4 cycle of the input, thus indicating a capability of providing a Doppler frequency accuracy of better than one cycle. An accuracy of one part in ten thousand is obtained with multistation missile tracking Doppler systems such as DOVAP. Because of the lack of any really dependable system to calibrate the accuracy of the DOPLOC system, the orbit determination error is not known with a high order of precision. However, based on the agreement between the orbital parameters determined by DOPLOC data and Space Track data, the DOPLOC data appear to be as good as the Space Track data.

A prime feature of the DOPLOC system is the translation or heterodyning of the input radio frequency signal down to a frequency spectrum low enough in frequency to be recorded on magnetic tape. This translation is done without degradation of the signal-to-noise ratio or loss of intelligence from the original signal out of the antenna. Thus the Doppler frequency from any pass can be stored and played back through the tracking filter and entire data processing system in the event that any of the equipment items failed during real time.

A discussion follows of the problems of modifying the basic DOPLOC system just described to provide a system with the anticipated capability of detecting, identifying and orbit predicting of non-radiating objects in space.

B. Application to Passive Tracking

A passive tracking system with the capability specified by ARPA requires the very best of available techniques and demands components of the highest performance attainable within economic feasibility. The performance characteristics and parameter values proposed for the DOPLOC passive satellite tracking system, based on the state-of-the-art will be treated in this section.

The basic relation between range and the other parameters of a reflection system can be expressed as:

$$R = \sqrt{\frac{P_t G_t G_r \lambda^2 \sigma}{P_r (4\pi)^3}}$$

where: R = range, P_t = transmitter power, P_r = receiving power, G_t and G_r are transmitter and receiving antenna power gain, λ = wave length and σ = effective reflection cross section.

It is of interest to solve for the range of a system using all high performance, state-of-the-art components for which known techniques of fabrication exist even though they may not be economically feasible or attractive at this time. Optimum parameters will be used in order to obtain a theoretical maximum performance from which performance in practice can be predicted by applying expected degradation factors. Under these conditions a transmitter of one megawatt is possible; transmitting and receiving antenna gains of 20 db each are reasonable since they are associated with moderately wide coverage, shaped radiation patterns of about $6^\circ \times 60^\circ$. A threshold received power requirement of 2×10^{-20} watts will be assumed, although seldom possible to attain in practice because of external noise sources, wider bandwidth requirements and initial lock-on requirements. Maximum range will be computed with three target sizes, 0.1, 1.0 and 10 square meters, covering most of the expected target sizes.

For σ = 0.1 sq. meter

$$R = \sqrt[4]{\frac{1 \times 10^6 \times (2.78)^2 \times 0.1 \times 100 \times 100}{2 \times 10^{-20} \times (4\pi)^3}}$$

$$= 3740 \text{ Km}$$

$$= 2330 \text{ miles}$$

For σ = 1.00 sq. meter

$$R = \sqrt[4]{10} \times 2330$$

$$= 4140 \text{ miles}$$

For σ = 10 sq. meters

$$R = \sqrt[4]{10} \times 4140$$

$$= 7370 \text{ miles.}$$

As previously stated these ranges are the maximum ones theoretically possible under optimum conditions. In practice several economic and technical factors enter to modify the parameter values attainable. A discussion follows on the nature and magnitude of some of these factors as they apply to the DOPLOC Passive Tracking System.

1. Transmitter Power - P_t. The use of one-megawatt transmitters at 108 to 150 mc at this time appears to be well within the state-of-the-art and limited only by economic considerations. However, such transmitters have to be specially built and require up to 24 months lead time at a cost of at least $1,000,000 each, for the basic transmitter without the antennas, shelter, installation and power facilities. Since the fence was to be installed on a six-month crash program it was necessary to procure an existing transmitter. The largest available unit located was a 50-KW f.m. broadcast transmitter. Since the reduction in power from one megawatt to 50 KW reduces the range by only a factor of 2.1, the 50-KW transmitter was considered to be adequate to demonstrate the feasibility of the DOPLOC system in an interim installation.

2. Antenna Gain - G_t and G_r. In the original planning it appeared to be technically and economically feasible to utilize antennas with about 20 db gain and 6^o x 60^o fan-shaped beams. The closest thing immediately available was the Minitrack type antenna. It produced approximately the desired beam shape and was rated by the manufacturer at 18-db gain. The reduction from 20 to 18-db gain reduced the range by a factor of 1.25. Unfortunately, in practice in the field, the realized antenna gain was still somewhat less, apparently nearer 16 db. A factor which must be considered is that the rated gain of the antennas could not be realized in practice due to polarization rotation and misalignment between the antennas and the target. An average loss of 4.3 db has been estimated for this factor, reducing the range by 1.27. It is also impossible to orient the transmitting and receiving antennas and to shape their patterns to overlap at optimum gain over a large volume of space. This condition is caused by the geometry involved, which is due in part to the curvature of the earth. The antenna orientation is treated in detail in BRL Report No. 1055 October 1958, entitled "Doppler Signals and Antenna Orientation for a DOPLOC System" by L. P. Bolgiano. Three geographic locations along a great circle were chosen. Fort Sill, Oklahoma, was chosen for the transmitter, and White Sands Missile Range and Forrest City, Arkansas, for the receiving stations. The distance between Fort Sill and WSMR is 480 miles and from Fort Sill to Forrest City, 433 miles. The site locations are as follows:

	WSMR	FORT SILL	FORREST CITY
Latitude	33°42'18"	34°39'20"	35°00'54"
Longitude	106°44'16"	98°24'20"	90°45'50"
Great Circle Bearing	79°51'16"	84°32'29"	89°01'23"

Three antennas were located at each station. They are designated as the center, north and south antennas. The center antenna at Fort Sill had its ground plane horizontal and its long axis in an approximate north-south direction. This placed the broad dimension of the antenna beam in an approximate east-west direction. The north and south antennas were

oriented to direct the fan-shaped beams 20^{o} above the horizon. At the receiving stations, the three antennas were directed to have the axes of the beams intersect at a distance of 900 miles from the stations. The receiving antennas were therefore tilted toward the transmitting antennas. The above mentioned report (by Bolgiano) contains a detailed computation of the antenna orientation angles and reduces the installation instructions to a series of rotations about easily defined axes. The types of "S" curves to be expected from satellites flying various courses relative to the detection system are plotted. Doppler shift and rate-of-change of Doppler shift are computed and graphed for 108 megacycles per second signal reflected from a passive satellite. Orientation angles to converge the beam patterns of a transmitting and receiving antenna, each with a $76^{o} \times 8^{o}$ beam, are computed and listed in tabular form. Computational procedures are described in detail to facilitate further investigation. It is shown that a one square meter cross section satellite within the antenna beam patterns will be detectable to a range of about 1,000 miles. In field practice this value of 1,000 miles range was found to be too optimistic for small size satellites. The actual achieved range was nearer 500 miles. Bolgiano also shows that tracking filter bandwidths greater than 10 cps are required only for the closest approach of very close satellites.

3. Operating Frequency. The choice of an optimum frequency for a DOPLOC passive satellite tracking system required considerable study. The frequency of 108 mc was available and had been chosen for the early U. S. satellite work. Equipment was readily available in this frequency range. Thus it appeared expedient to set up the interim fence on a frequency of 108 mc. However this was not believed to be an optimum frequency or really even a good choice. The cosmic noise at 108 mc had been measured to be large enough at certain times to reduce the receiver system sensitivity by as much as 6 db, i.e. by a factor of 4 in power of 1.4 in range. The average cosmic noise level has been measured to be about 2 to 3 db above receiver noise with some periods of very little or no cosmic noise. At about the time of the initiation of work on the fence, the opinion of many radio engineers appeared to favor a much higher frequency than 108 mc.

This opinion was based on the fact that as the frequency of operation is increased the external noise, such as cosmic noise decreases. A more intensive investigation of this subject showed that, of the several factors having parameters which vary with frequency in the 100 to 1,000 mc range, the advantages and disadvantages as one increases frequency almost exactly balance each other out to such an extent that it was found that the best frequency range for a reflection DOPLOC system was between 100 and 150 Mc/s. As applied to the satellite fence program, the optimization of the frequency problem is one of choosing a frequency which will give a maximum probability, within technical and economic limitations of detecting non-radiating satellites. The maximum amount of transmitter power available for radiation is assumed to be fixed. The principal factors which affect the selection of the optimum frequency include the following:

1. Radar equation.
2. Antenna beam width requirements.
3. Cosmic and galactic noises.
4. Bandwidth
5. Minimum detectable signal.

The way in which these factors affect the choice of frequency to be used is discussed briefly in the following paragraphs.

a. Radar Equation. The radar equation for the reflection type Doppler signal is the combination of two equations, each of which presents the inverse-square power loss in one leg of the path from transmitter to satellite to receiver. It may be written in the form:

$$P_r = KG_t P_t A_s A_r / r_1^2 r_2^2$$

where P_r is the receiver power, K is an arbitrary constant, G_t is the gain of transmitting antenna, P_t is the transmitted power, A_s is the effective scatter area of the satellite, A_r is the effective area of the receiving antenna, and r_1 and r_2 are the distances from the satellite to the transmitter and to the receiver, respectively.

The value of A_s is limited in its maximum value by the physical projected area of the satellite. Consequently the ratio of A_s to r_1^2 has a limiting value set by the physical size of the satellite and by the range. Similarly, on the receiving path, the solid angle within which energy is received from the satellite is determined by the ratio of the effective antenna area to the square of the slant range, r_2^2. The larger the effective area of the receiving antenna, therefore, the larger is the magnitude of the signal received at the receiving site for any given magnitude of transmitted power and antenna gain at the transmitter and receiver. The effective capture area of a receiving antenna, of fixed gain, decreases as the frequency increases. Therefore, as the operating frequency is increased, the received power will decrease, based on capture area considerations.

b. Antenna Beamwidth. The beam angular dimensions for both the transmitting and the receiving antennas for a satellite detection system such as DOPLOC must be established on the basis of the orbital parameters of the satellite and the minimum data requirements for an orbital solution. The solid angle within which the system is to receive energy from a satellite must intersect the solid angle through which energy from the transmitter is radiated, and it must be of such dimensions that the probability of recognition of a satellite passage is high. The numerical specifications of angular dimensions explicitly determine the gain and the dimensions of the antenna in wave lengths. To obtain a maximum capture area from such an antenna, it is again desirable to use the lowest possible frequency. Otherwise, maximum energy capture is not achieved, and the objective of maximum range is defeated. Increasing the antenna area in square wave lengths and using higher frequencies (keeping the physical area approximately constant) produces narrower beam widths than those required to permit the total required amount of data, with the result that the received signal will not have sufficient duration. Beamwidth considerations therefore also favor low frequencies.

c. Cosmic Noise. Cosmic and galactic noise is made up of electromagnetic disturbances or signals having characteristics similar to white noise. When, however, these signals are examined over a wide frequency range they lose some of the similarity to white noise. Consequently, the equivalent black body temperature of the radiation varies with the frequency of measurement, decreasing from between 2,000 to 20,000 degrees Kelvin at 64 mc/s, depending on the sky area, to less than 100 degrees at 910 mc/s. (True white noise characteristics would result in a constant temperature as a function of frequency.) The effective sky temperature has been reported by Maxon[1*] to change at different rates with respect to frequency, depending on the area of the sky which is being observed. The frequency and the temperature have an inverse exponential relation, the exact value of the exponent depending on whether the measurement is made in the direction of the galactic plane or not. The equation applying when looking toward the center of the galaxy is given as:

$$T_w = K_g f^{-2.7}$$

where T_w is the equivalent black body temperature, K_g is the constant of proportionality for the galaxy, and f is the frequency in mc. A similar equation is given for outer cosmic areas:

$$T_w = K_c f^{-2.1}$$

where K_c is the constant of proportionality of cosmic space. A single exponent of -2.3 is given by Cottony[2] of the National Bureau of Standards which gives an overall average relationship of

$$T_w = Kf^{-2.3}$$

Superficially, the rapid reduction of T_w with frequency would make it appear that the higher the frequency used, the better the results. This is not necessarily the case, since it has been shown that the desired signal will also decrease as the frequency increases. Since the received signal falls off as the inverse square of the frequency, the new increase in signal-to-noise ratio varies exponentially with frequency between -0.1

* Superscripts refer to references at the end of the report.

and -0.7 based on the cosmic noise consideration alone. There is also filter bandwidth effect to be considered which requires an increase in bandwidth by the square root of the frequency increase which tends to balance out the cosmic noise fall-off, depending upon which exponent is used. Figure 1 shows the variation of minimum detectable satellite signal (S/N = 1) as a function of frequency, assuming a value of 100 mc as a reference, both for areas of the sky toward the galactic center (toward sagittarius) and toward the pole of galaxy (extragalactic). The minimum level is shown for two cases, constant signal bandwidth and bandwidth proportional to the carrier frequency.

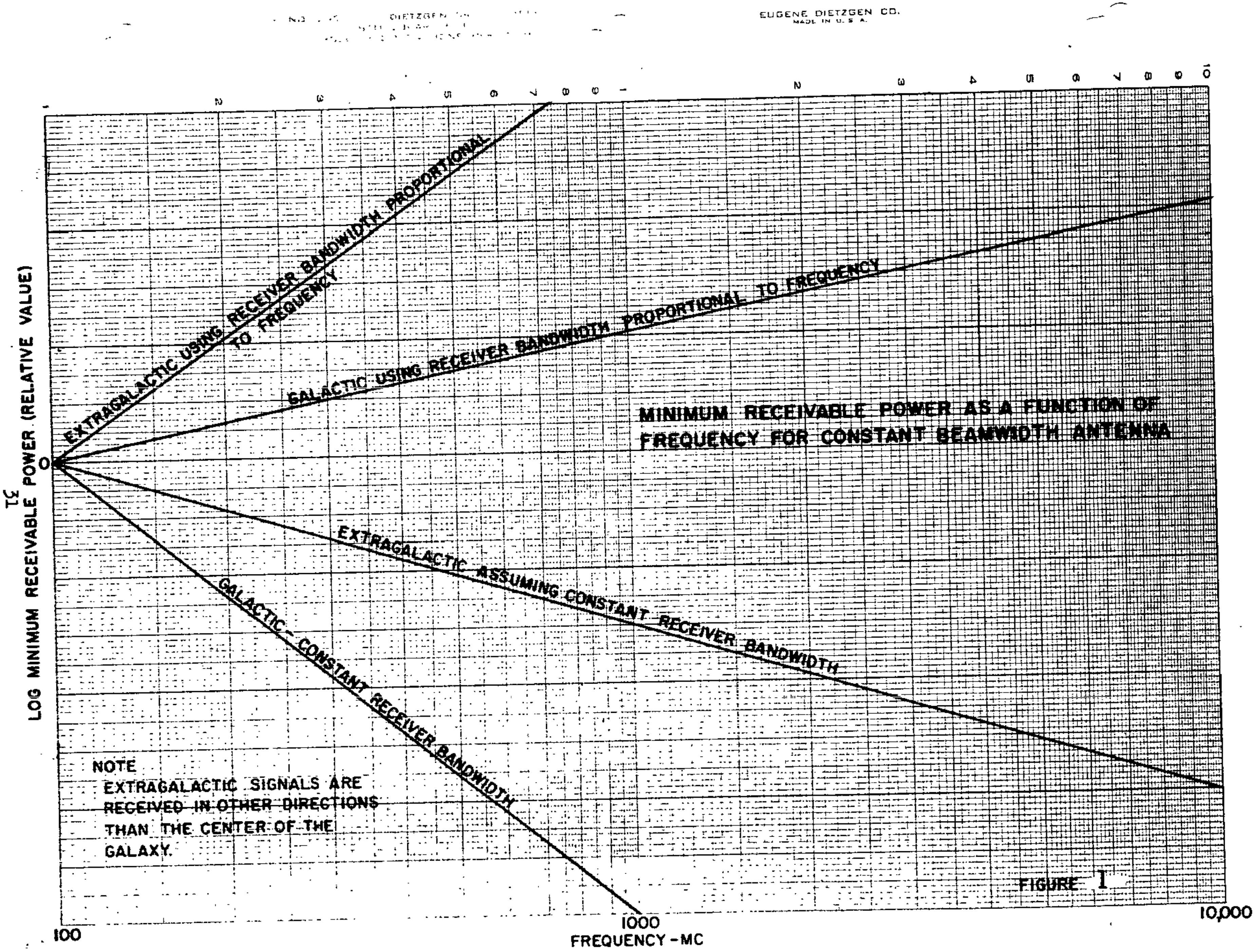
The minimum signal requirement in the presence of cosmic noise is derived by converting the cosmic noise level, which is given in equivalent sky brightness or black body temperature in degrees Kelvin, to power density in watts per square meter. This conversion, based on the Rayleigh-Jeans law, is as follows:

$$p = \frac{8\pi K f^2 B T w}{C^2}$$

where p is in watts per square meter, K is the Boltzman constant, f is in cps, B is bandwidth in cps, Tw is the black body temperature in degrees Kelvin, and C is the velocity of propagation. Black body radiation is randomly polarized, with equal power in each plane, therefore a linearly polarized receiving antenna will intercept only one half of the power given by the above expression. It is significant to note with regard to the above equation that the noise power density is proportional to the square of the frequency. The net effect of increasing the operating frequency is the combination of this factor with the fall-off of cosmic noise with frequency as follows:

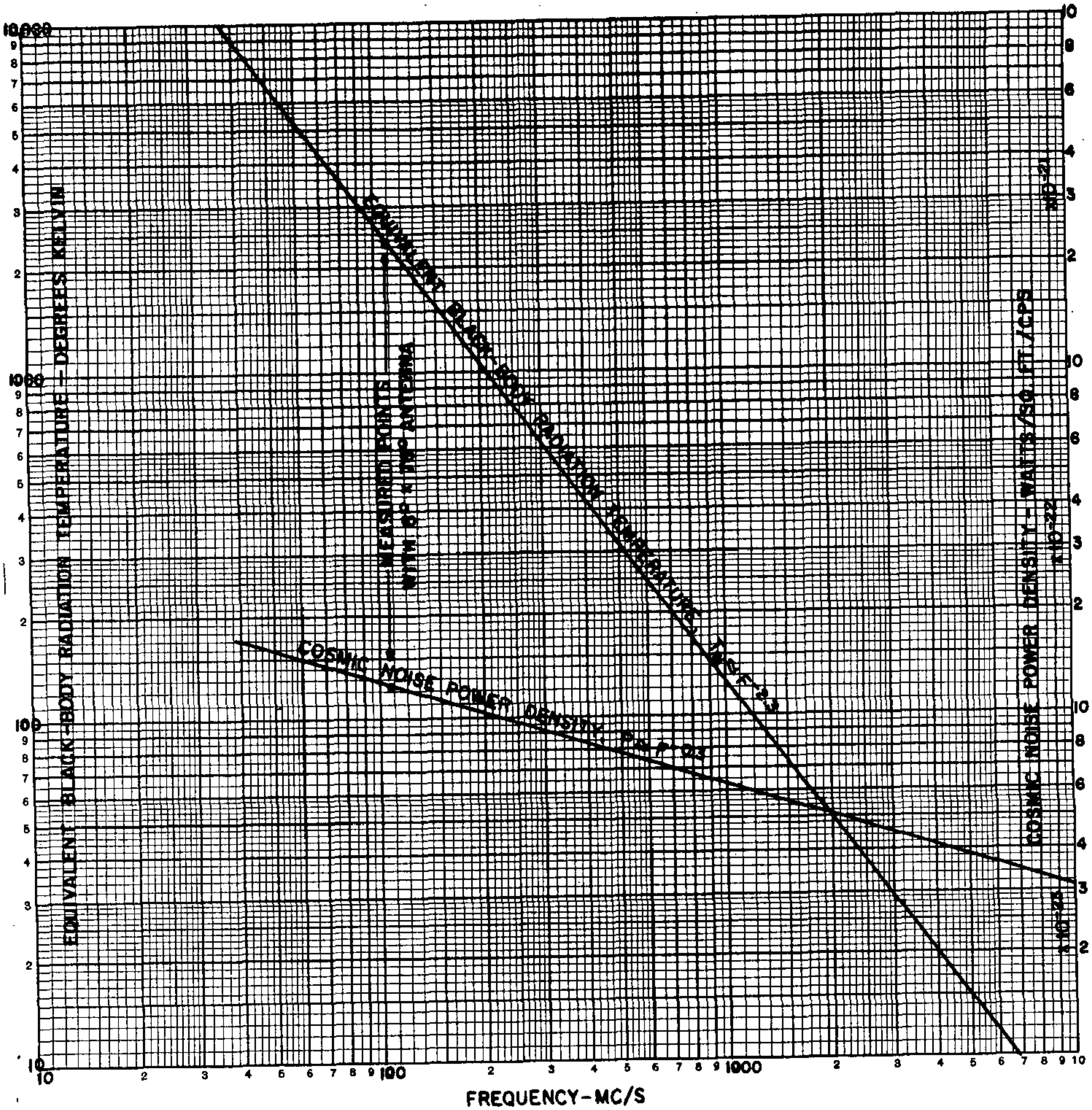
$$\begin{aligned} P &= K' f^{-2.3} \times f^2 \\ &= K' f^{-0.3} \end{aligned}$$

These relationships between black body temperature, power density and frequency are shown in Figure 2 using measured values at 108 mc as



EXTRAGALACTIC USING RECEIVER BANDWIDTH PROPORTIONAL TO FREQUENCY
GALACTIC USING RECEIVER BANDWIDTH PROPORTIONAL TO FREQUENCY
MINIMUM RECEIVABLE POWER AS A FUNCTION OF FREQUENCY FOR CONSTANT BEAMWIDTH ANTENNA
EXTRAGALACTIC ASSUMING CONSTANT RECEIVER BANDWIDTH
GALACTIC - CONSTANT RECEIVER BANDWIDTH
LOG MINIMUM RECEIVABLE POWER (RELATIVE VALUE)
0
NOTE
EXTRAGALACTIC SIGNALS ARE RECEIVED IN OTHER DIRECTIONS THAN THE CENTER OF THE GALAXY.
100
1000
10,000
FREQUENCY - MC
EUGENE DIETZGEN CO.
MADE IN U. S. A.

FIGURE 1



COSMIC NOISE VS. FREQUENCY

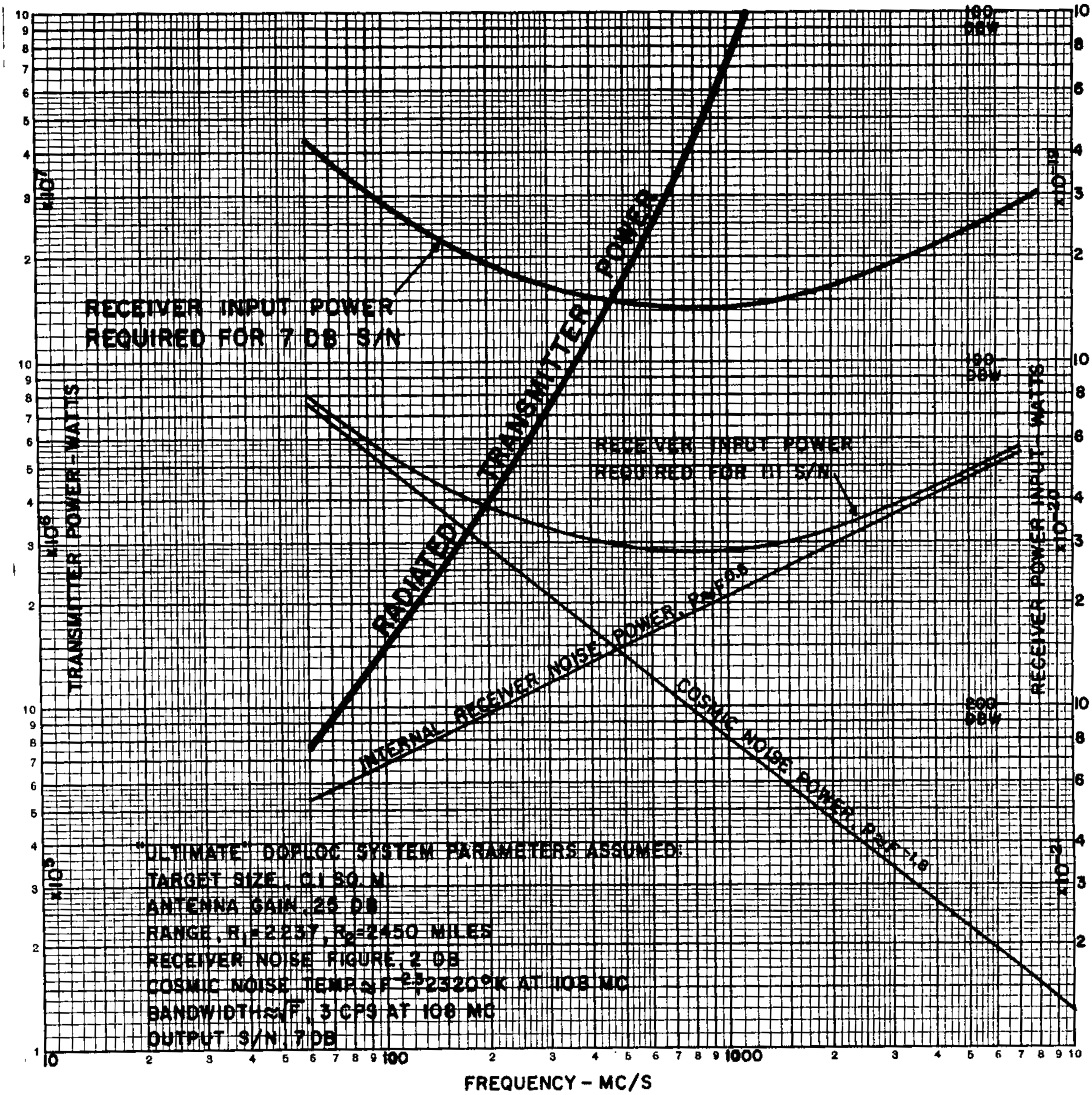
FIGURE 2

reference points. These plots show that there is a quite small decrease in cosmic noise power density with frequency. A ten-to-one increase in frequency reduces the cosmic noise power density by only a factor or two.

In summary, the exact manner in which cosmic noise varies at the output of the antenna or the receiver after passing through the bandwidth limiting circuits, is strongly dependent upon the basic type of tracking system under consideration. The interim DOPLOC system required a fixed antenna beam width and increasing bandwidth with frequency, therefore the optimum frequency based on cosmic noise consideration is a low frequency. Figure 3 summarizes the effect of cosmic noise with a plot of the relation between receiver signal power required, transmitter power, and carrier frequency. The saving in transmitter power by operating at low frequency is shown in this graph. The major opposing factor not shown on the graph is the increasing height of the antenna structure as the frequency is decreased. This can be a critical factor since the cost of unusually high structures increases roughly as the cube of the height.

d. Bandwidth. The information bandwidth required for tracking the Doppler frequency signal reflected from a satellite is proportional to the square root of the carrier frequency. Since the signal-to-noise ratio is the critical factor in satellite detection, both a minimum bandwidth and minimum operating frequency consistent with other conditions must be accepted for optimum results. Fundamentally, the filters for all tracking systems must have sufficient bandwidth to encompass the random phase noise and higher derivative signal components. For this reason, the lowest frequency which has negligible ionospheric noise should be used.

e. Minimum Detectable Signal. The introduction of narrow band tracking filters and of new types of low noise receivers has stimulated an interest in determining what physical parameters really limit the detection of a coherent signal. Qualitative arguments had been advanced suggesting that quantum limitations might exist at power levels within the capabilities of modern radio receivers. Accordingly it was considered of interest to investigate whether quantum mechanical considerations set limitations to



RECEIVER SIGNAL INPUT POWER AND
TRANSMITTER POWER VS. FREQUENCY

FIGURE 3

achievable sensitivities and to evaluate their engineering importance. A small contract designed to support an investigation of the probable quantum limitation of detectable signals was awarded to the Electrical Engineering Department of the University of Delaware, Newark, Delaware, with Dr. L. P. Bolgiano, Jr. and Prof. W. M. Gottschalk as the principal investigators. This work was reported in "Quantum Mechanical Analysis of Radio Frequency Radiation" by L. P. Bolgiano, Jr. and W. M. Gottschalk, Report No. 13 in the BRL DOPLOC Satellite Fence Series, June 15, 1960, Electrical Engineering Department, University of Delaware, Newark, Delaware. In this report an intuitive account of thermal radiation, making complementary use of classical wave and particle descriptions, is used to give a qualitative introduction to the nature and magnitude of the effect which might be expected. Quantum mechanical computations of the phenomena obtained in specific detectors and preamplifiers are reviewed and found to support the observability of quantum fluctuations. It is found that the random signals observed in wide band radiometers are sufficiently weak to make these quantum fluctuations of comparable magnitude to classical wave fluctuations if receiver noise is ignored. It is also shown that the specific power level at which quantum levels become important may depend strongly on the information to be extracted from the signal. For the purpose of this discussion relative to frequency selection for DOPLOC, it should suffice to say that if the quantum mechanical limitation should prove to be a limiting factor, it can be expected that the minimum detectable signal power will be proportional to the square of the frequency, and will thus mitigate in favor of a low DOPLOC carrier frequency.

f. Conclusions Relative to Choice of Frequency. The considerations presented above indicate that the optimum frequency for the DOPLOC system should be as low as is consistent with the bandwidth required to accommodate ionospheric noise. Experience with the analysis of DOVAP (Doppler) and satellite tracking records at BRL indicates that, because of the ionospheric background noise modulation on the signal, the probable minimum bandwidth setting on a tracking filter operated at 76 mc is approximately 5 cps, where as for signals at 108 mc it is approximately 2.5 cps. Since the maximum

bandwidth, from consideration of missile signal dynamics, which might be required to lock on to the satellite at an altitude of 500 miles is 4.5 cps, and at 2500 miles, 1.4 cps, and after lock on, some one or two cycles would be required to track, it is evident that operation at 76 mc shows the presence of an excessive amount of noise, whereas operation at 108 mc is perhaps an excellent compromise. Actually, as indicated above, a reasonable broad band of frequencies may be considered essentially optimum since the loss of sensitivity with frequency is shown by the Figure 3, page 34, to vary at a rate of $f^{0.3}$ to $f^{0.7}$ relation. On the basis of the data shown, the range within which the frequency should be selected extends from 100 to 150 mc with 175 mc as the highest permissible value. Thus 108 mc was quite suitable for the interim fence system. For the ultimate DOPLOC system which was proposed but never instrumented, a frequency of 150 mc was chosen.

4. Receiver Power Sensitivity. An effort was made to design the receiver circuits to provide a signal sensitivity of 2×10^{-20} watts when used with a 1 cps bandwidth. Under controlled conditions and with the antenna pointed in low noise directions, this sensitivity was actually obtained. However it is not practical to attain such high sensitivity and narrow bandwidth in tracking earth satellites at 100 to 1,000 miles altitude and at 108 mc frequency. As previously noted, cosmic noise power will on the average double the required power for reception. Also passive satellites at 100 - 1,000 miles altitude require more bandwidth than 1 cps to accommodate only the dynamics of the problem. The highest sensitivity is needed when searching at low elevation angles to detect satellites as they emerge over the horizon. This is compatible with the information bandwidth required since the rate-of-change of frequency is then smallest, permitting the use of the narrowest bandwidth. Wider bandwidths are required to maintain lock-on as the satellite passes by the station, particularly at the lower altitudes. This again is compatible since the distances are shortest and sensitivity requirements least at closest approach.

Any automatic lock-on system for use with the tracking filter requires a signal about three db greater for capture or lock-on than is required to hold lock and track once the signal is locked on. This is because of the

fast rates at which the lock-on device must sweep in frequency in order to cover the spectrum to be searched. Thus a total of approximately 6 db increase in signal may be required in practice above that assumed in previous range calculations. This can cause a further range reduction of approximately 1.4. In summary, the received power required for locking onto a signal, under different conditions of bandwidth and cosmic noise is tabulated as follows:

Received Signal Power Required	Bandwidth, cps	Cosmic Noise Level
10^{-19} watts (-190 dbw)	2.5	Negligible
2×10^{-19} watts (-187 dbw)	2.5	3 db above receiver noise
10^{-18} watts (-180 dbw)	25	Negligible
2×10^{-18} watts (-177 dbw)	25	3 db above receiver noise.

5. Satellite Reflection Cross Section - σ . Since the DOPLOC system had been initially designed for use with radiating (active) satellites, there was really no problem in obtaining the required signal strength from very small missile borne transmitters over the altitude range and from horizon to horizon. To adapt DOPLOC to the small signals which would be reflected from small bodies of 0.1 to 10 square meters effective reflection cross section required a careful study of signal levels to be expected from practical transmitter powers and realizable satellites. Body configurations, dimensions, spin, tumble, and extent of camouflage all affect the reflection cross section of a body. The term "effective" cross section is used to mean the value of σ in the radar equation that must be used to determine the actual range of propagation with the particular satellite target under consideration. The effective reflection cross-section area is strongly affected by the alignment of the target's reflection amplitude pattern and polarization with respect to the illuminating and receiving station antennas. By using the equations available in the literature for the monostatic case, i.e., transmitter and receiver coincident, the effective dimensions of

simple spheres and cylinders were calculated. The values thus obtained were for peak reflection cross section with optimum orientation of the target on the maximum of the reflection pattern lobe. Calculated values for spheres and cylinders are as follows:

Max. Cross Section	Sphere Dia.	Cylinder Length
0.1 sq meters	1.5 feet	2 1/4 feet
1.0	4.2	3 1/2 feet
10.0	11.7	14 to 50 feet.

The areas for the cylinders were computed for a length-to-diameter ratio of 15. A range of 14 to 50 feet was estimated for a cross section of 10 square meters because of the effects of resonance. If the effective length of the target happens to be an exact multiple of a half wave length, it will have a much larger effective area than if it is some random length. For the bistatic case, where the transmitter and receiver are widely separated compared with the range of tracking, the angle between the incident and the reflected rays further modifies the effective cross section area. Power and effective cross section area calculations are treated in more detail in BRL Report No. 1330, entitled "DOPLOC Observations of Reflection Cross Sections of Satellites" by H. Lootens. Using the DOPLOC data and the equation $\sigma = \frac{\pi de^2}{\lambda}$ and the basic radar equation, effective cross section areas were computed for a number of satellites that were tracked. The computations are based on actual, measured data. To give an idea of the magnitude and ranges of effective cross section area, the data below are taken from Lootens' report. In the original data effective cross section areas are computed for the center, north, and south antennas when sufficient data are available. Since the principal interest here is to show the extent of the variation in reflection cross section, data from the center antenna only are given.

TABLE II - 1

Effective Cross Section Area for Selected Satellites and Revolution Numbers

SATELLITE	Revolution No.	(Cross Section Area (sq. ft.)) Measured in Center Antenna
'58 Delta	7049	86.0
	7358	47.0
	8386	68.5
	8643	25.6
	8683	87.9
	8719	27.1
	8734	28.2
	8795	15.1
	9009	40.5
	9172	49.0
	9255	178.2
	9286	248.0
	9466	87.1
	9472	292.0
	9503	22.9
	9581	38.0
	9716	16.2
	9826	12.7
	9832	7.1
	9848	22.3
	9938	180.0
	9943	74.5
	10001	29.6
'59 Epsilon	53	26.6
	60	18.8
	314	14.7
	414	70.2

TABLE II - 1 (Cont.'d)

SATELLITE	Revolution No.	(Cross Section Area (sq. ft.)) Measured in Center Antenna
'59 Zeta	14	132.0
	556	27.7
	855	59.3
	871	51.2
	884	151.2
'59 Kappa	183	225.6
'59 Lambda	96	102.2
	138	60.5
	278	149.8
	1285	174.4
	1516	72.9
'60 Gamma 1	318	94.5
	403	63.3
	418	46.4
	836	118.0
	960	97.1
'60 Gamma 2	1042	32.4
'60 Delta	30	35.9
	124	53.1
	140	20.9
	156	10.6
	165	71.5
	172	210.0

TABLE II - 1 (Cont.'d)

SATELLITE	Revolution No.	(Cross Section Area (sq. ft.)) Measured in Center Antenna
'60 Epsilon 1	165	303.7
	386	81.0
	522	206.1
'60 Epsilon 2	137	23.5
	147	14.0
	303	14.0
	309	96.0
	616	6.2

6. Reflections from other Objects. It was initially expected that both airplanes and meteors would produce spurious reflections which might be troublesome to eliminate from the DOPLOC data. Since it was known that Stanford Research Institute personnel had made an extended study of reflections from meteors and meteor trails, advantage was taken of an existing contract with SRI to have this problem studied. The effects of meteors and meteor trails are discussed in detail in a report "DOPLOC System Studies" by W. E. Scharfman, H. Rathman, H. Guthart, and T. Morita (Final Report, Part B, Report No. 10 in the BRL DOPLOC Satellite Fence Series), Stanford Research Institute, Menlo Park, California.

In practice, meteors enter the atmosphere with velocities between 10 and 75 kilometers per second. Although some meteors are decelerated noticeably in the atmosphere, most of them evaporate and deposit their ionization along their path at a nearly constant velocity. While a meteor is coming in, an echo is received from the elemental scattering lengths of ionization formed along the straight-line path of the trail. This "Doppler echo" has the range and velocity of the meteor at the start of the ionization trail, and shows a considerable Doppler shift which depends on its velocity and on its orientation with respect to the transmitter and receiver. The echo from the meteor itself is normally too small to be

directly detected, so that the detected signal is due to the reflection from a trail which is increasing in length with time. The amplitude of the echo rises to a large value at the point (if any) where the angle formed by a ray from the transmitter and the normal to the trail axis is equal to the angle formed by a ray from the receiver and the normal to the trail axis. After the meteor has passed this point, referred to as the specular point, the received signal is composed of a Doppler echo superimposed on a continuing specular echo from the body of the trail near this point. The "body echo" decays while remaining at a more or less fixed range, and shows only a slight Doppler shift caused by ionospheric winds. Thus the head echos were at very high Doppler frequencies and were unable to pass the tracking filter, while the echos from the trails showed little or no Doppler slope. These could easily be identified as trail echos and presented no data reduction problem.

During the entire observation period approximately 10 so called unidentified bodies were indicated in the DOPLOC data. These data had the proper Doppler frequency change for satellites, but did not correspond to any known orbits. They may have been caused by meteors or could have resulted from equipment malfunctions, or possibly even unidentified bodies. No data are available to indicate the seriousness of the problem of discriminating against meteor signals when the scanned beam antennas are used as proposed for the full scale system. However it appears that this problem can be easily solved by limiting the range of Doppler frequency which can be locked in on the tracking or circulating memory filter

7. Solutions for Orbit Parameters. When the interim DOPLOC fence was first conceived, the only problem which had not already been essentially either solved or for the solution of which known engineering techniques were available, was that of determining the orbital parameters from DOPLOC data. The three or four station DOVAP problem had been solved with consistency and accuracy for years. But in the DOVAP problem the missile carried a transponder and a minimum of three stations with reasonably good station location geometry were available. The goal set for the DOPLOC

system was to determine an orbit with sufficient accuracy to either identify a satellite as a known one or as a new one from data obtained from a single pass over a single receiving station and in a time after detection of less than one pass or orbit period. The first efforts seemed to be rather hopeless, but by the end of the second six-month reporting period a method was sufficiently well developed to be included in the second technical summary report. More recently, an extensive effort, both in house and by contract, has resulted in the development of satisfactory methods of solution. These methods will be treated in some detail later in this report.

III. DOPLOC EXPERIMENTAL FACILITY

A. Background Experience and Developments

Since 1945, when BRL first established the DOVAP instrumentation at White Sands Missile Range, New Mexico, the Ballistic Measurement Laboratory had been actively working toward extending the range and dependability of trajectory data gathering equipment. Through a contract with Convair the DORAN equipment was developed in an effort to remove the ambiguity from the Doppler data. By contract with Ralph M. Parsons Company a reflection Doppler system was developed for measuring the velocity of missiles, specifically artillery shell, at short ranges. This was a strictly passive system and had inherently many of the problems that were later to be encountered in DOPLOC. Another trajectory data gathering system which was developed and demonstrated, but which has never been used extensively, was called SPHEREDOP. In addition to the system development work, BRL had devoted considerable effort to the development of special narrow band tracking filters, high gain radio receivers and stable oscillators or constant frequency sources. The problem of receiving low energy signals in the presence of high noise levels had been studied extensively. Such problems as attempting to eliminate the effects of spin and attitude change from the DOVAP data had led to special techniques in signal reception.

Within a few hours after the Russians announced the launching of the first Sputnik satellite, BRL had established a tracking station and was supplying data to other interested agencies. These data were of course only active data from the satellite's own radio transmitter. However narrow band techniques and many of the features later built into the DOPLOC system were employed. Thus, when ARPA asked for a satellite tracking facility, BRL had already developed a considerable competence in the detection of low energy signals in the presence of noise.

In May 1958 BRL proposed to establish, in co-operation with the Naval Research Laboratory, a satellite detection and tracking facility. This total facility would extend across the southern United States in an east to west direction from coast to coast at about latitude 32° N. The Naval

Research Laboratory would provide sections of what was later called a fence, extending from the east coast to about the Mississippi River, and from the west coast eastward to near White Sands Missile Range, New Mexico. BRL would provide the center section extending from White Sands Missile Range to Memphis, Tennessee. This proposal was approved by ARPA and resulted in ARPA Order 8-58 dated 20 June 1958. This order directed BRL in co-operation with the Minitrack satellite tracking system to produce the capability of detecting, identifying and orbit predicting of non-radiating objects in space. The only specific direction contained in the order relative to the nature of the facility was that BRL would establish a Doppler system complex. The method of reporting to ARPA and an indication of the funding to be expected were contained in the order.

BRL personnel realized that no facility or developed technique within the United States existed which was capable of meeting the proposed performance specifications suggested by the Gentry committee. Briefly this specification called for detecting and tracking all objects having effective reflection cross section areas greater than 0.1 square meter to altitudes of 2,000 miles. The plan of attack was therefore to establish an experimental facility with a minimum range capability and to establish engineering studies and research projects as required to develop a specification for a full scale DOPLOC system. Following this plan BRL launched a crash program to install in the field an interim facility within a period of six months beginning approximately 1 July 1958. Immediate action was taken to collect together the applicable equipment that was available in BRL and to place orders for such equipment as could be bought directly "off-the-shelf". As fast as the problems could be analyzed sufficiently to prepare scopes of work, negotiations were started toward contracts with other research facilities.

B. Interim Experimental Fence

In making plans for the interim fence, the choice of an operating frequency was one of the first actions required. Since 108 mc was available for the Minitrack equipment under the Geophysical Year Program, and

since a quick study showed this frequency to be close to optimum, and with that equipment already designed, 108 mc was chosen for the interim fence. Theoretical and practical considerations leading to and confirming the wisdom of this choice of frequency were summarized at some length in section II of this report.

Another early problem concerned the choice of station sites. The upper end of White Sands Missile Range and Fort Sill, Oklahoma, were found to be close to the desired great circle path and about the proper distance apart to cover the distance between WSMR and Memphis with one transmitter for illumination and two receivers for detection. Since land and many other facilities were readily available on the Government owned and operated facilities, it was decided to use WSMR and Fort Sill as two of the stations and to locate a third near Memphis, Tennessee. A great circle from WSMR to near Memphis through Fort Sill ran through Forrest City, Arkansas, and just south of Memphis. Since most of the land just south and southwest of Memphis is either heavily populated or else very low river bottom land which is subject to flooding, the Forrest City area was chosen as a probable, good location for one receiving station. A high section of land known as Crowly's Ridge runs just east of Forrest City, Arkansas. A hilltop one mile from the town proved to be an excellent location. It was close to power and water, yet far enough from developed areas and traveled roads to be quiet from the point of view of electromagnetic noise. The radio transmitter station was then located at Fort Sill and the other receiving station near Stallion Site near the upper end of WSMR. As it turned out, the Fort Sill and Forrest City site choices were excellent. The White Sands Missile Range site left much to be desired. This location was too isolated, being twelve miles from Stallion over undeveloped desert trails. Stallion was itself 35 miles from the nearest village where housing could be obtained. Although the site was probably quiet in so far as man-made electrical interference was concerned, it was plagued with sand storms, sand static and power failures. Long power and signal lines were required with the attendant line failures. Sand leakage in the building also caused some damage to moving equipment, tape recorders, relays, etc. Sand also tended to foul up the cooling system and prevent proper cooling of electronic equipment.

As a research station and a quick and ready place to try out ideas experimentally, BRL retained and improved the active satellite tracking station at Aberdeen Proving Ground. This station was moved from a temporary shack to a permanent type building located on Spesutie Island. This facility has proven to be very useful both to BRL personnel working on the DOPLOC system and to the missile firing agencies working at Wallops Island and at Cape Canaveral. Figure 4 is a rough outline of the United States and indicates the positions of the DOPLOC stations.

The design of the station buildings and antenna fields was turned over to the Little Rock Office of the U. S. Army Engineers. Using drawings from Little Rock, the Albuquerque and Tulsa Offices of the U. S. Army Engineers contracted for and supervised the construction of the WSMR and Fort Sill stations. The Little Rock Engineers contracted for and supervised the construction of the Forrest City station. The two receiving stations were housed in prefabricated metal buildings. These buildings were 24 x 100 feet single story structures, set on concrete slabs. The transmitter occupied a prefabricated metal building which was 20 x 80 feet, also on a concrete slab. In addition a 20 x 12 foot garage building of sheet metal was provided for an auxiliary generator at the transmitter building. Since the generator was never procured, the garage was utilized for a storage facility. Figure 4a shows an exterior view of the transmitter building.

Since it was contrary to BRL policy to assume routine operational responsibility for a project such as the fence, the Signal Corps was requested to plan to assume responsibility for the operational phase when and if a suitable installation became available. In addition the U. S. Army Signal Engineering Agency was requested to install the radio transmitter at Fort Sill. After installation by USASEA the operational phase was to be turned over to the U. S. Army Communications Agency. This agency assumed control of the transmitter station and furnished a station supervisor and teletype operators. At the receiving stations USACA furnished station supervisors and teletype operators. Since the equipment at the stations later became a research facility, USACA withdrew from the operation when it became apparent that no routine operational phase would develop. Except for the station supervisors and teletype operators the stations were manned by Philco Technical Representative contract employees.

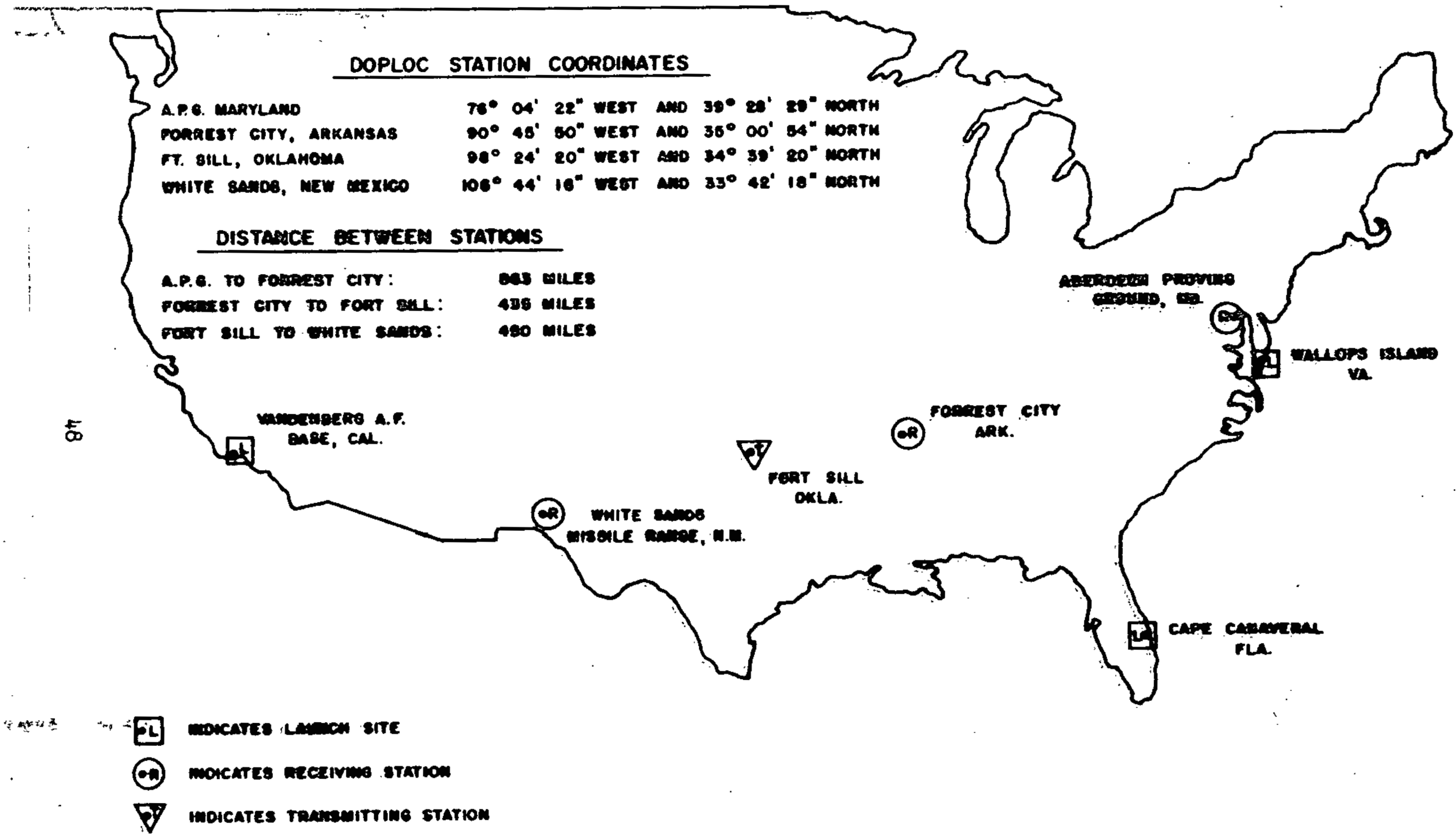


FIGURE 4 LOCATION OF DOPLOC TRACKING STATIONS

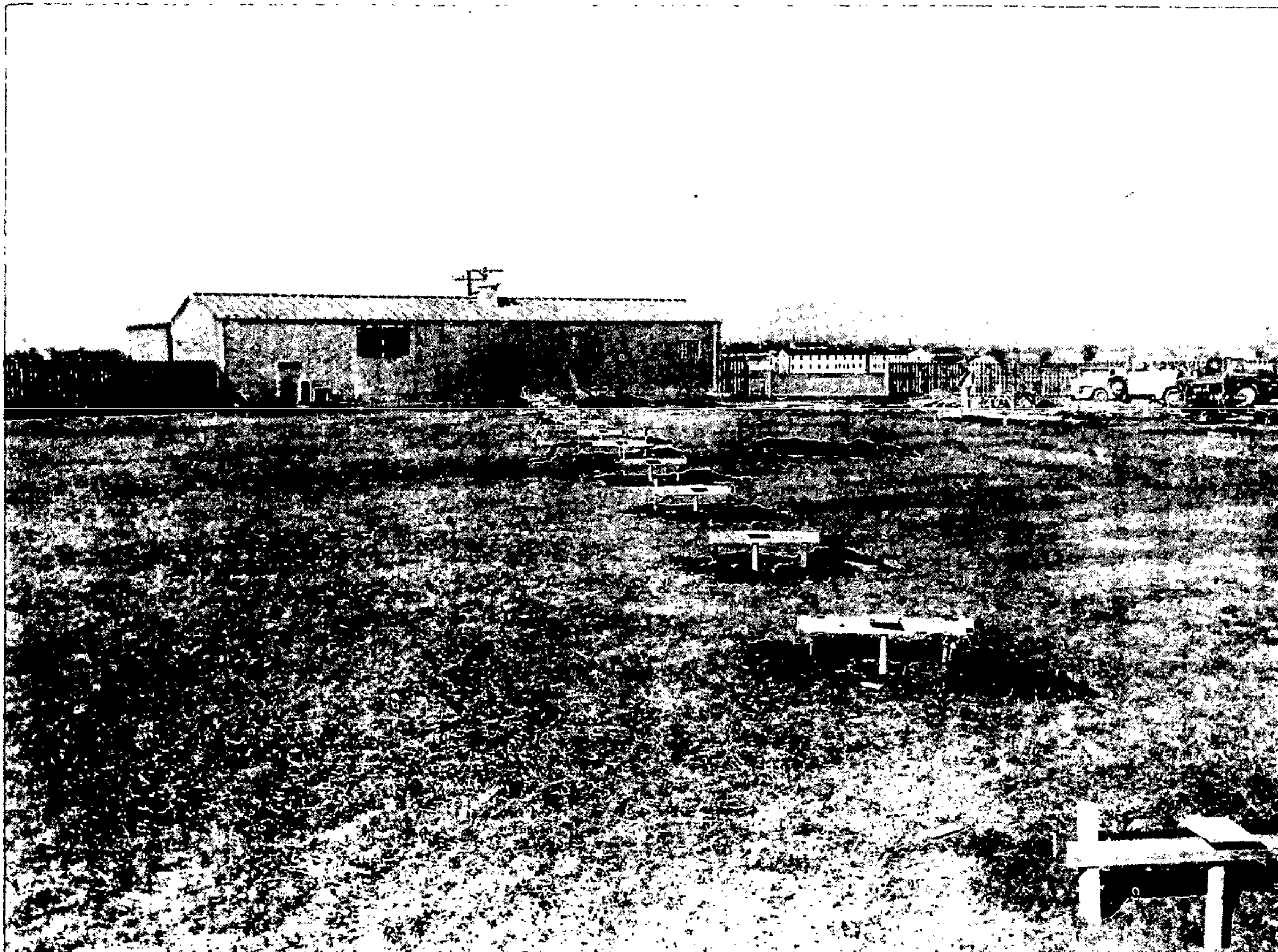


Figure 4a DOPLOC Transmitter Building

1. Radio Transmitter. In the DOPLOC satellite detection and tracking system, a high power radio transmitter is used to excite a narrow beam antenna which in turn illuminates a satellite to cause radio frequency energy to be reflected back to a receiving antenna. To meet the six month installation period, it was necessary to utilize existing equipment, since the lead time for fabrication of any reasonably high power transmitter would exceed six months. A used commercial 50-KW transmitter, manufactured by Westinghouse Corporation was located in storage. Since it had been built several years previously, a contract was arranged with the Gates Radio Corporation to remove the f.m. modulation equipment and to completely refurbish the transmitter. Since the DOPLOC system requires a very stable frequency source for determining the transmitter frequency, the original frequency standard or oscillator and the low power frequency multiplier and amplifier stages were replaced with a high stability frequency standard, phase stable multiplier and low power amplifiers. This exciter equipment was engineered and fabricated by the U. S. Army Signal Engineering Laboratory, Fort Monmouth, New Jersey.

Since the frequency standard which served as the basic frequency source for the transmitter had an instability of one part in 10^9 or less over a period of thirty minutes to one day, a precise method of frequency measurement and monitoring was required. The frequency measuring equipment at the transmitter station consisted of a second precision frequency standard, the radio receiving and frequency comparison equipment required to compare the standard's frequency with that of the National Bureau of Standards' standard frequency transmissions, a time code generator, a real-time counter and a ten-megacycle-per-second counter. Figure 5 is a block diagram of the transmitter and frequency measuring system. Figure 6 is a photograph of this equipment. Figure 7 and Figure 8 are two views of the transmitter installation.

The code generator and real-time counter served as an electronic clock indicating hours, minutes and seconds in digital form with the accuracy of the basic frequency standard. Using code pulses and a calibrated oscillographic sweep, the time counter was synchronized with WWV signals to plus

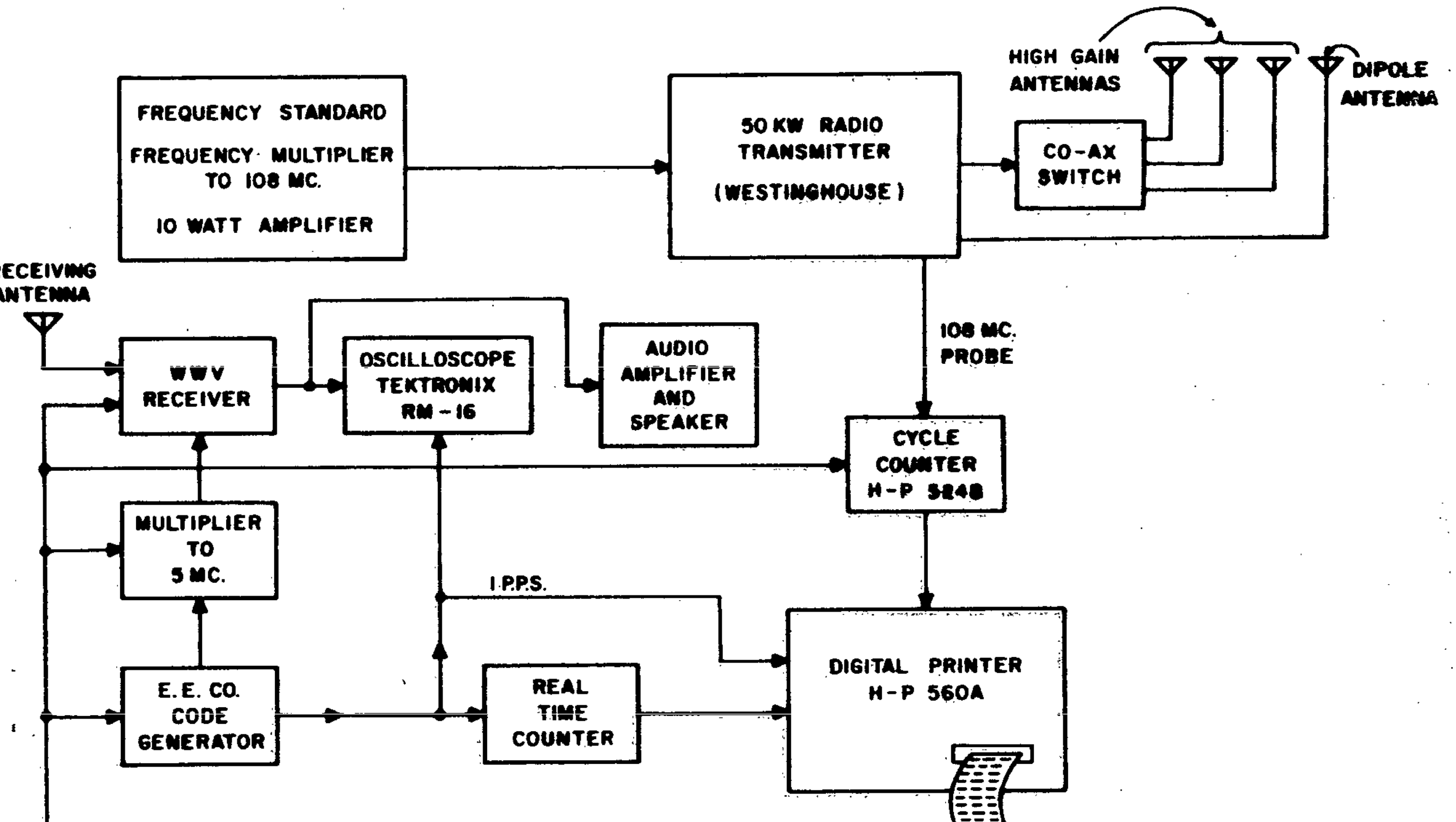


FIGURE 5 DOPLOC SYSTEM 50 KW RADIO TRANSMITTER AND FREQUENCY MEASURING EQUIPMENT

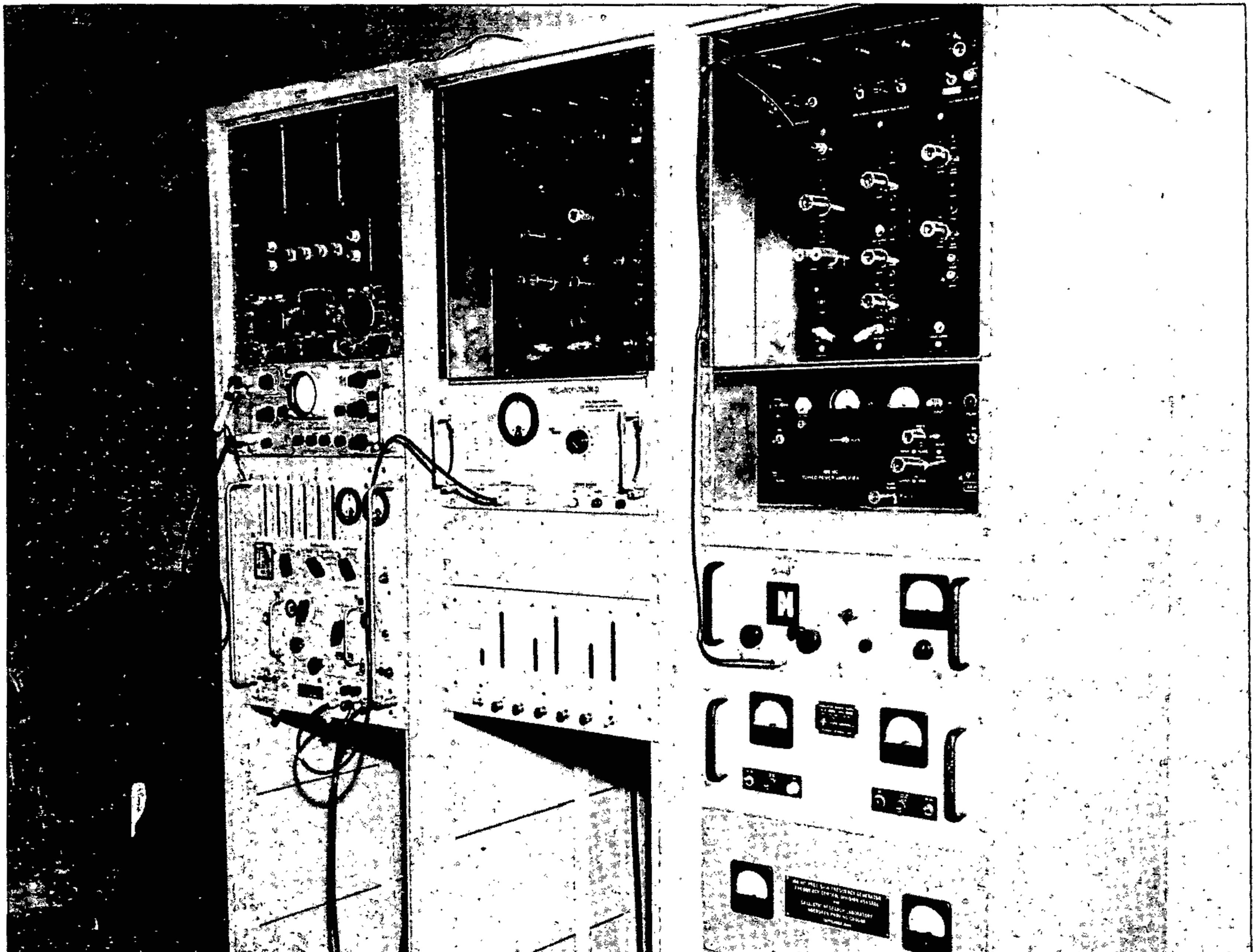


Figure 6 Photograph of Frequency Generating and Measuring Equipment

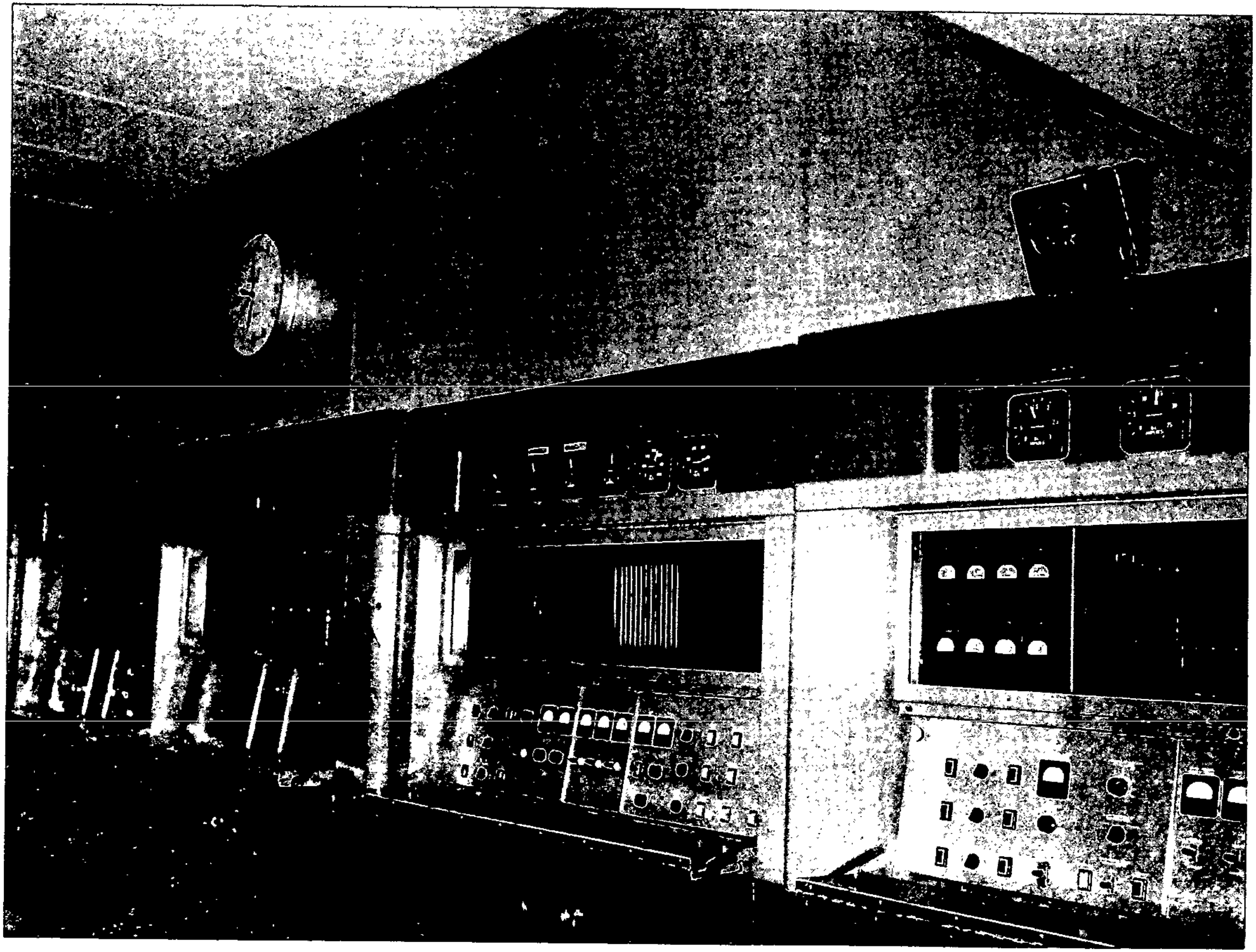


Figure 7 View of Front of 50 KW Transmitter

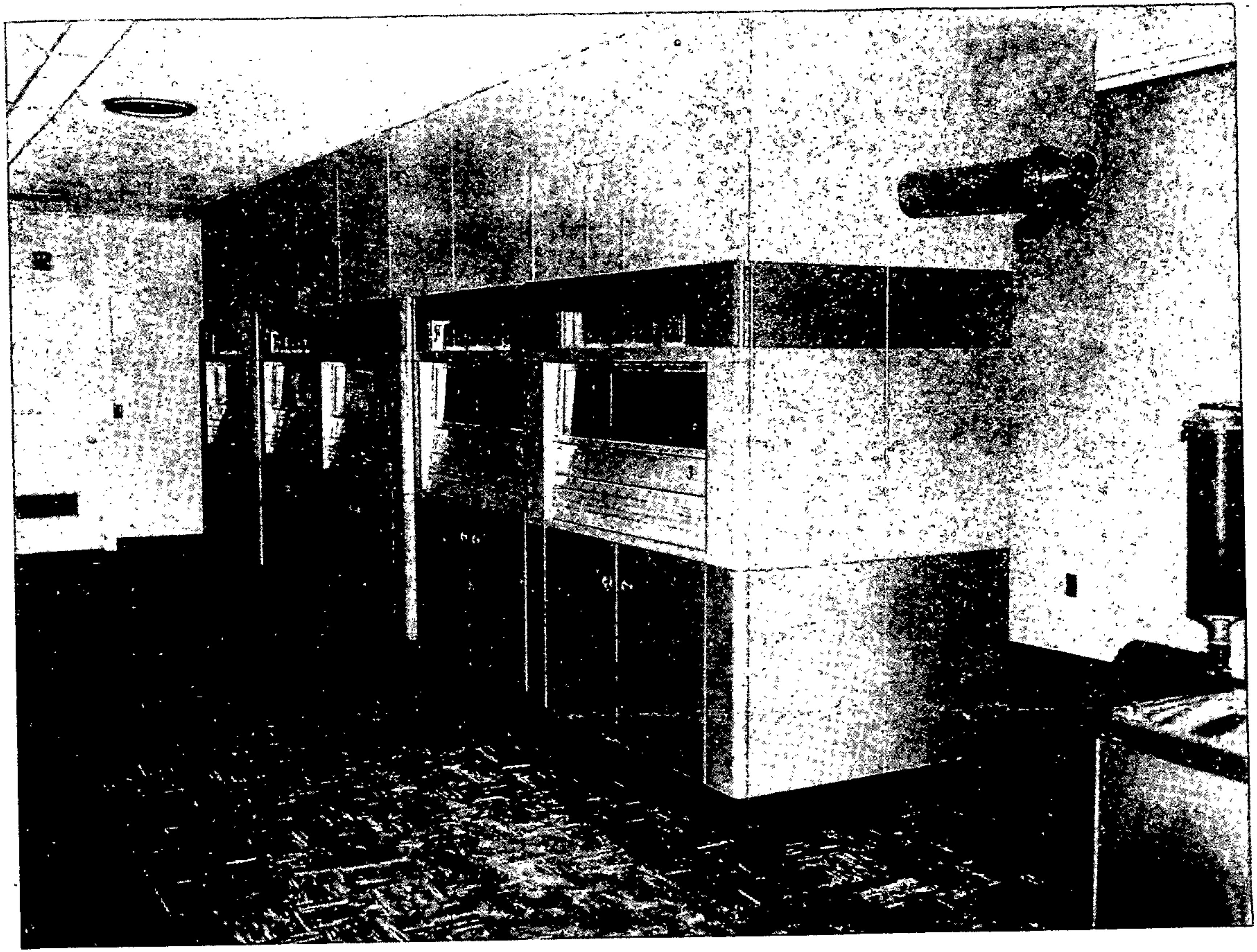


Figure 8 View of 50 KW DOPLOC Transmitter - 50 KW Cubicle is in Foreground

or minus one millisecond. This counter's output was printed out on the first six wheels of a Hewlett-Packard, model 56-A digital printer once each second, or oftener, at the choice of the operator.

The output of the frequency standard, calibrated with WWV, served as a time base for the ten-megacycle-per-second counter, H.P. model 524B. An r.f. probe from the output amplifier of the transmitter supplied a 108-mc signal which was fed to this cycle counter to obtain a frequency measurement. The output of the first five digits of the cycle counter was fed to the remaining five digit wheels of the printer where it was printed out on command by control pulses from the time code generator. Thus, the printed record contained the transmitter frequency to an accuracy of plus or minus one cycle, with real time data, at intervals as small as one second. A half-duplex, leased, commercial teletype line connected the transmitting station to all the receiving stations and to the computation center at the Ballistic Research Laboratories, allowing either manual or tape transmission of the transmitter frequency data.

The output of the transmitter was fed to a system of motor driven, remotely controlled, coaxial cable switches which provided for switching the transmitter power to any of the three high gain antennas. The antennas were located 200 feet from the transmitter and fed through 6 1/8" diameter coaxial cable. Each antenna radiated a fan shaped beam having a solid angle coverage of 76 x 8 degrees. Orientation of the antennas is shown in Figure 9. The beam from the center antenna was directed vertically with its 76-degree dimension in the east-west direction. The center of the north antenna beam was rotated to 20 degrees above the horizon with the 76-degree dimension in the north-east to north-west sector, while the south antenna was similarly inclined to the south.

This arrangement was designed to permit acquisition and tracking of a satellite soon after it appeared above the horizon, and then switching to the other two antennas in succession for tracking through their respective beams to obtain three segments of the typical Doppler "S" curve. Tilting and rotational adjustments were provided in both the transmitting and receiving antennas to provide for aligning the beams to view and illuminate the same space.

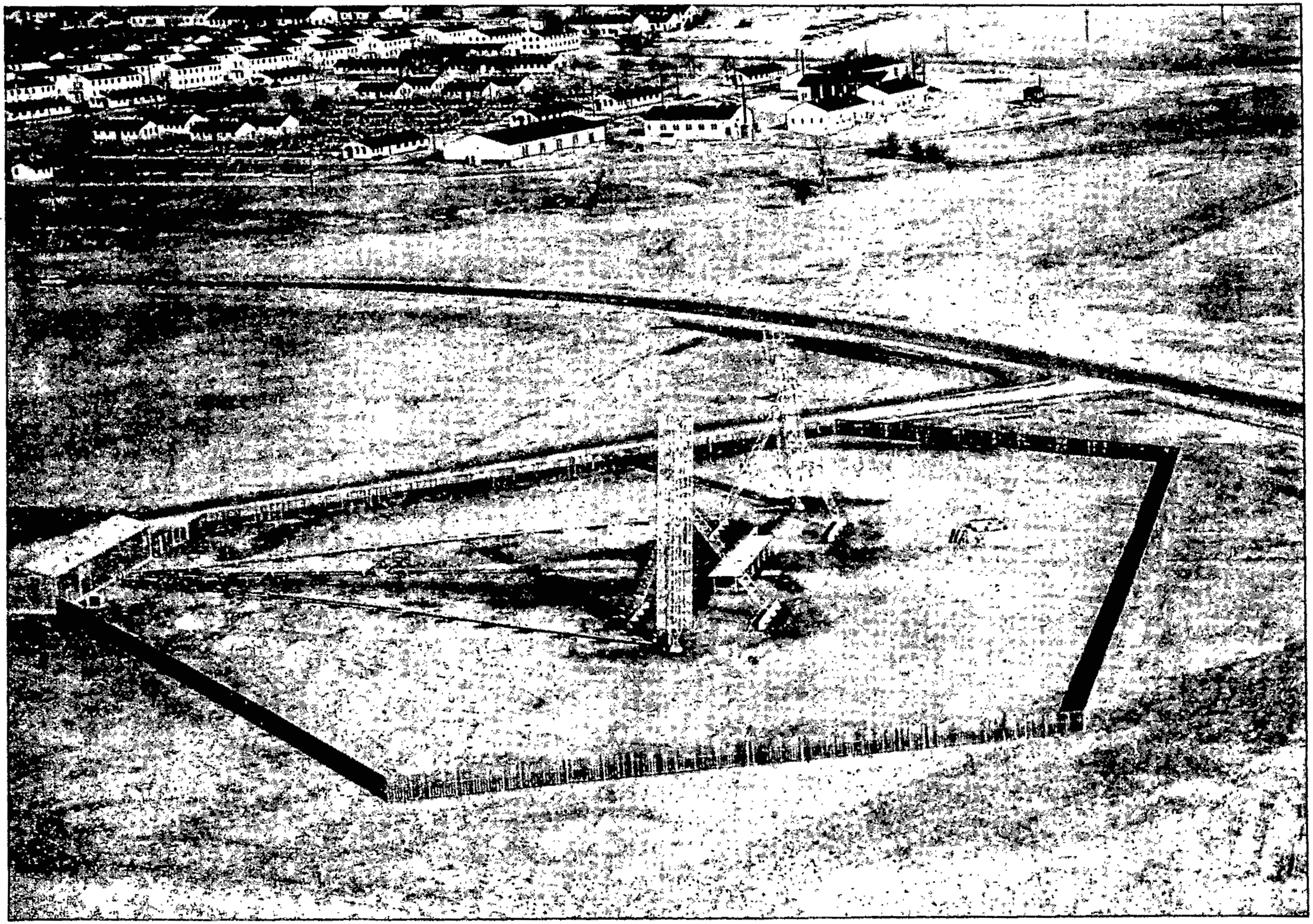


Figure 9   Orientation of Transmitting Antennas

In order to provide complete test facilities and also to get the transmitter into operation as soon as possible, a single dipole antenna was mounted over a concrete service pit on a copper sheet ground plane. This antenna was used for a few weeks before the high gain antennas were delivered. However, it had limited power handling capacity of about 25 KW because of an improperly designed section. The dipole was never used after the high gain antennas became available. Extra precaution was taken to provide an adequate ground plane system and good earth grounds in both the transmitter building and the antenna field. A special duct and blower system was provided to cool the transmitter in summer and to conserve some of the transmitter heat to heat the building in winter.

2. DOPLOC Receiving Station Interim - Radio Frequency Circuits. When the interim DOPLOC fence equipment was being planned, radio receivers which operated directly at 108 mc were not immediately available. A system of preamplifiers and converters was therefore used to reduce the frequency to the tuning range of a standard type R-390A radio receiver. A BRL built preamplifier operating at 108 mc was connected between the antennas and a Tapetone Model TC-108 converter. Early in the program transistorized, stabilized, crystal oscillators were used at 61.2 mc and the frequency doubled to 122.4 mc to convert to 14.4 mc at the input to the R-390A receiver. Another standard frequency source was used for the conversion frequency in the receiver. The frequency biased Doppler signal was then fed to the tracking filter and to the magnetic tape recorder. Later in the program, Borg frequency standards became available as frequency sources. Rohde and Schwarz frequency synthesizers and decade frequency multipliers became available for conversion purposes. These were very convenient since any frequency over extremely wide ranges could be obtained to an accuracy of 1 cycle per second and an instability of less than one part in 10^9. Figure 10 is a basic block diagram of the r. f. section used in the interim DOPLOC station. A 108-mc crystal-controlled signal generator was loosely coupled to the antenna or connected to a dipole antenna for a built-in sensitivity calibration.

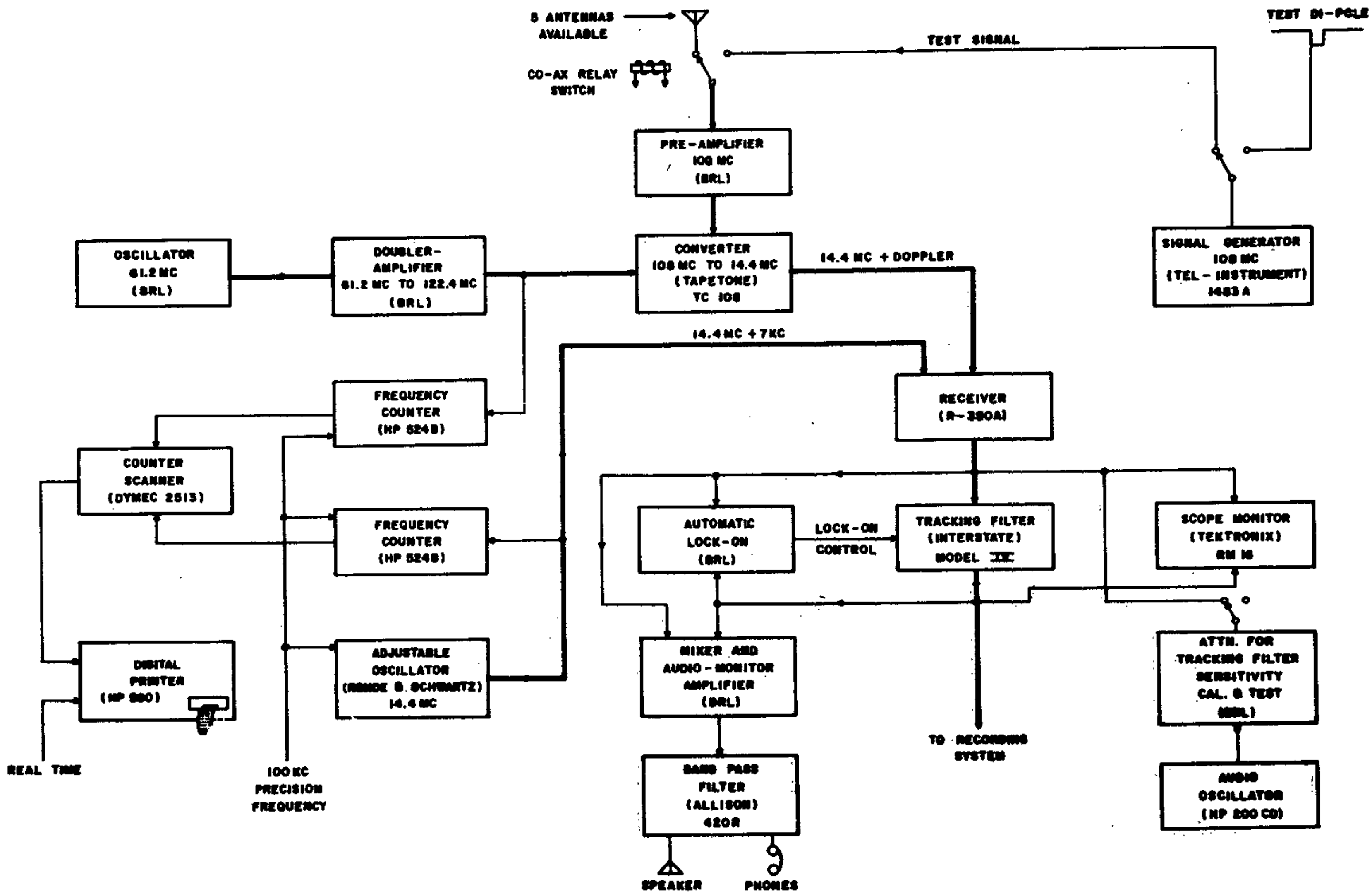


FIGURE 10 BLOCK DIAGRAM OF R.F. SECTION IN DOPLOC STATION PASSIVE TRACKING AT 108 MC

Figure 11 shows a block diagram of the equipment used for active tracking, (Radiating satellites). Four channels of receiving equipment were available in each station. One channel could work directly into the encoders and teletype equipment thence back to the computing laboratory. Other records which occurred during record transmission were magnetically recorded and transmitted sequentially. Each receiving station was also provided with receiving equipment capable of receiving from active satellites over a wide range of frequencies, actually from 20 mc to 960 mc. In general just one channel of equipment was available at these special frequencies. BRL Report No. 1123 entitled "DOPLOC Instrumentation System for Satellite Tracking" by C. L. Adams describes in detail the mechanics of the instrumentation.

For extending the frequency range from 55 to 900 mc, a Nems-Clarke radio reciever and a range extension unit, model REU-300-B were used.

3. Automatic Search and Lock-on. One of the most ingenious developments of the DOPLOC system was an automatic signal search and lock-on device which automatically placed the tracking filter on any signal occurring within the search range of the equipment. The energy reflected from a satellite is weak and usually imbedded in noise. For a passive system to perform defense surveillance requires 24-hour-a-day operation with maximum detection sensitivity and the shortest possible reaction time. Manual searching requiring constant operator attention would cause excessive operator fatigue and greatly reduce the detection capability of the system. The short duration and low signal strength of the signals would limit the operation of the tracking filters. Signals far down in the noise would require excessive time to identify and lock on manually. Therefore an automatic search and lock-on system was found to be necessary. The automatic lock-on (ALO) described below overcame the limitations of manual operation and provided a fully automatic search facility. The following basic requirements were established for the ALO:

a. The chosen audio frequency band, in this case 12 kc must be searched in a minimum time.

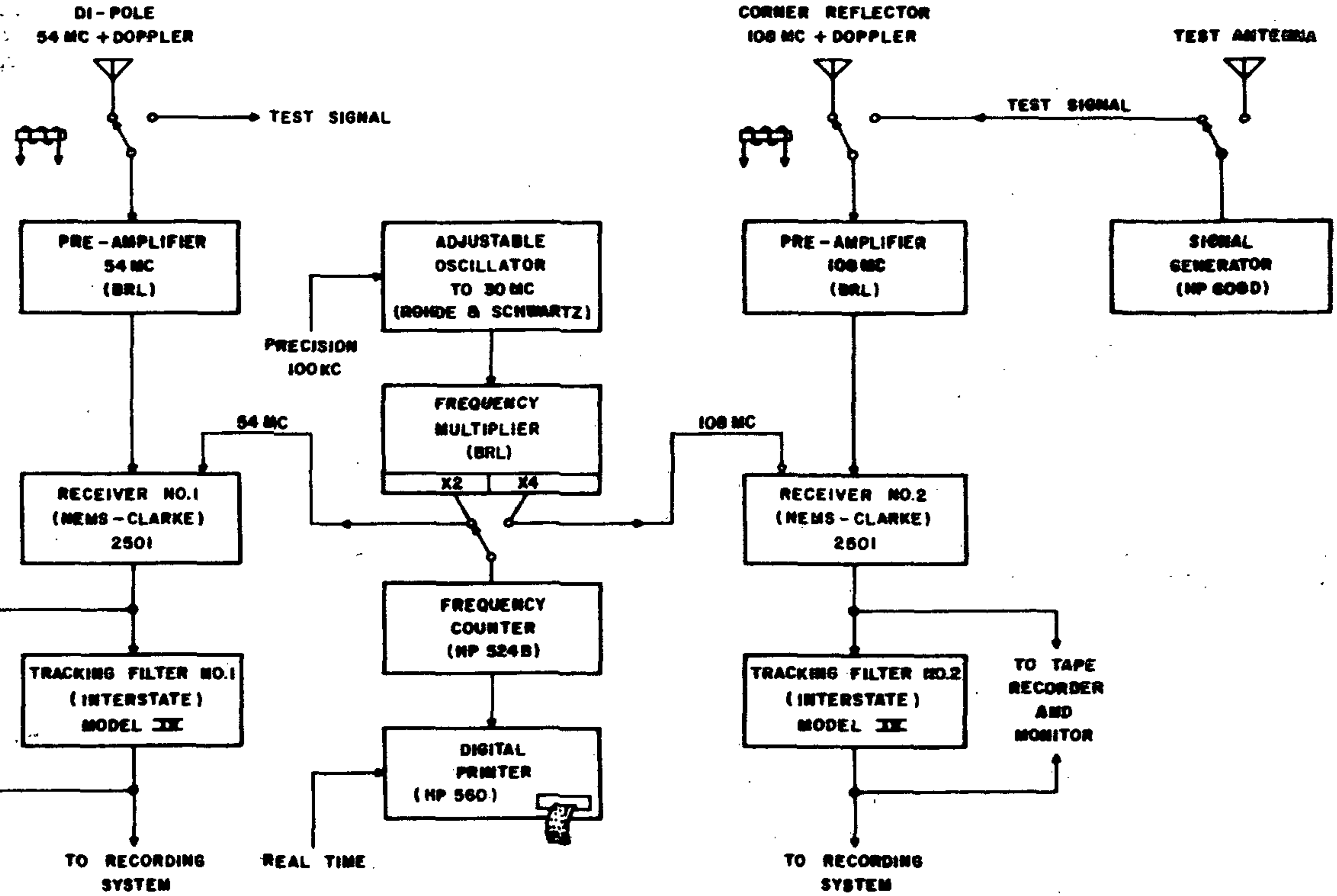


FIGURE 11 BLOCK DIAGRAM OF R.F. SECTION FOR ACTIVE TRACKING
(2 CHANNELS OF 4 AVAILABLE AT APG, MD.)

b. The system must be capable of finding the smallest theoretical signal determined by the search bandwidth.

c. The time (known as acquisition time) required to recognize and use the signal that is present in noise must be held to a minimum.

d. The system must position the tracking filter oscillator to the desired frequency and place the filter in a lock condition.

A block diagram of the ALO system is shown in Figure 12.

To meet the requirements of minimum search time, ten filters of fixed bandwidth were placed in the desired audio frequency band and the signal frequency swept across the filters. The ten fixed filters were each spaced 100 cycles per second apart to cover a one-kc band, compatible with tracking filter bandwidth characteristics. These filters were then switched twelve times to cover the full 12-kc band. The rate of switching determined the time available to find a signal as well as the total sweep time. Three switching rates were used, 2.5, 5 and 10 cps. When the 10 cycles per second rate was used, the time for each 1-kc band was 100 milliseconds and for the whole band 1.2 seconds. The mixing and switching techniques employed in the ALO removed the requirement for 120 individual oscillators or ten switchable oscillators normally needed for coverage at 100-cps bandwidth from 2 to 14 kc.

Each filter consisted of a mixer (which had the output of an oscillator for one input and the input signal plus noise for the other), a low pass filter and a control relay. The low pass filters were variable in fixed steps from 0.5 to 50 cps. The part of the frequency spectrum viewed by each filter was the oscillator frequency plus or minus the bandwidth of the low-pass filter. Shifting the oscillator frequency allowed switching of the filter to cover another frequency band. The oscillators were placed 100 cps apart and covered a 1-kc band. The oscillator frequencies were switched in groups of ten from two to three kc, three to four kc and so on to 13 to 14 kc. Serial pulses necessary for gating and switching were derived from a counter with a count cycle of 12. A frequency generator chassis using 1 kc and

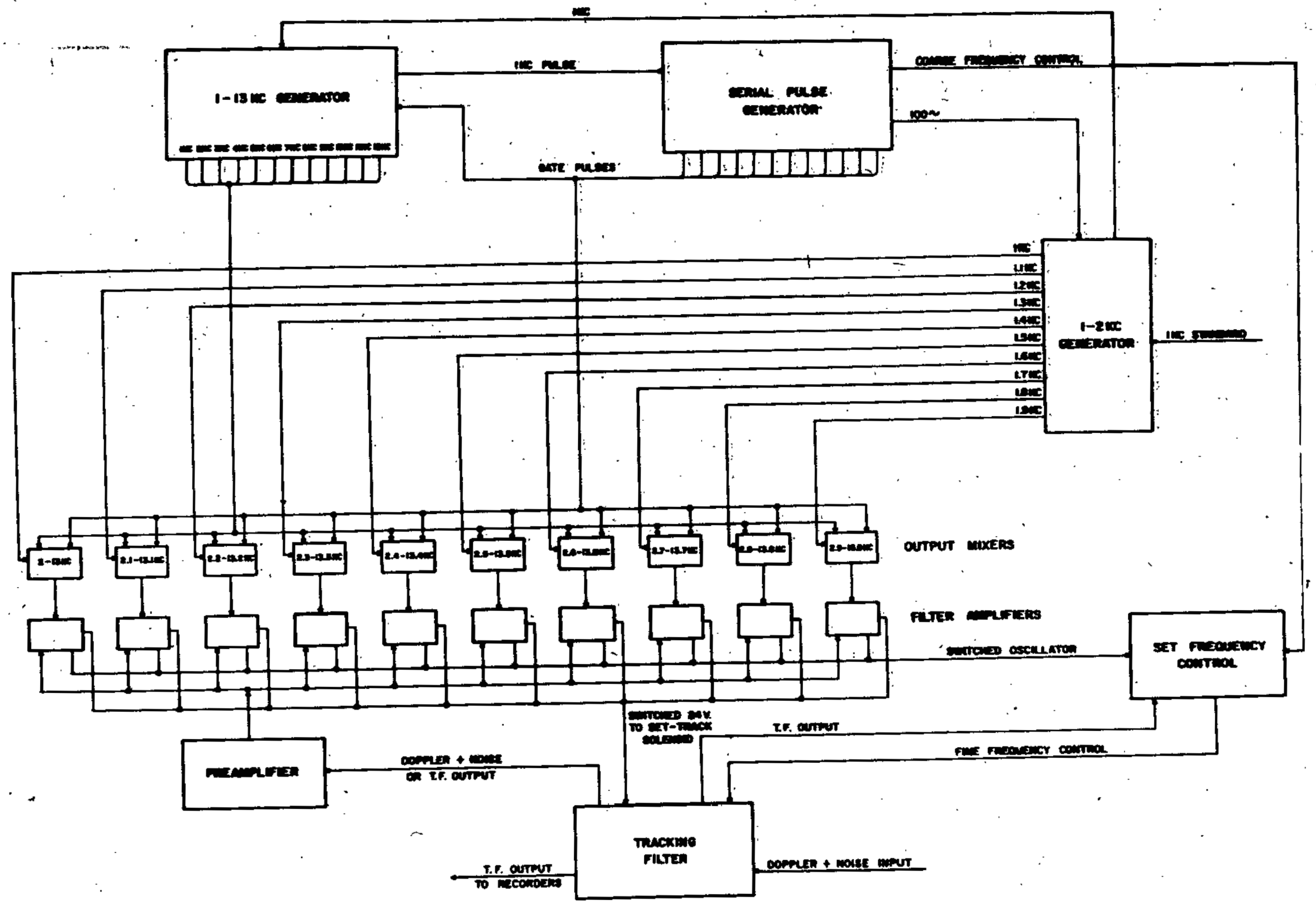


FIGURE 12 BLOCK DIAGRAM OF AUTOMATIC LOCK-ON SYSTEM

100 cps inputs, obtained from the stations timing system, provided the multiplication and mixing to produce 10 simultaneous output frequencies. Each pulse from the counter changed the signals being mixed and shifted the range by 1 kc. If a signal was present in the noise in the frequency range from 2 to 14 kc, of sufficient amplitude, and within the bandwidth of one of the oscillators, it activated one of the filters.

After the presence and the frequency of a signal was indicated by the ALO, the phase-lock tracking filter had to be correctly positioned. In the track position, an internal oscillator was locked to the input signal by the use of a feed back loop. The automatic lock-on circuits used an external loop around the tracking filter in the set position to lock the oscillator near the input signal. The fixed filter, upon receiving a signal, closed its control relay with one set of its contacts, putting the oscillator frequency of the fixed filter into a circuit termed the "set frequency" control. This circuit was part of the external loop and compared the fixed filter oscillator frequency with the tracking filter oscillator frequency and generated an error voltage which was applied to the tracking filter and controlled its oscillator to produce a phase-lock between the two oscillators.

In the automatic system, the "set track" switch in a standard tracking filter was replaced by a rotary solenoid. At the time the fixed filter oscillator was applied to the "set frequency" control, voltage was also applied to the solenoid. The tracking filter was positioned to the correct frequency before the solenoid moved to the track position. In the track position, the tracking filter loop was closed and a phase lock was obtained between the internal oscillator and the true input signal.

4. <u>The Phase-lock Tracking Filter</u>. The phase-lock tracking filter used in the interim DOPLOC system was the Model IV as supplied by the Interstate Electronics Corporation, Anaheim, California. This tracking filter was the result of several BRL developmental contracts starting with the development of PARDOP by the Ralph M. Parsons Company, Pasadena, California. It was an electronic bandpass filter whose center frequency

was made to track automatically the frequency of the input signal. This was accomplished with a very tight, phase-locked, servo-controlled circuit. A very large signal-to-noise improvement was obtained by the use of an extremely narrow filter bandwidth relative to the input circuit bandwidth. Figure 13 is a block diagram of the tracking filter system with the basic closed loop system shown in heavy lines.

The input Doppler signal was fed to the input mixer where it was subtracted from the VCO output frequency to result in a 25-kc signal. This was amplified in a tuned i.f. stage of about 250-cps bandwidth. The amplified signal was then fed to the main phase detector where it was compared in phase with the output of a 25-kc fixed frequency crystal oscillator. Utilizing a cross-correlation type detector and equalizer network, the oscillator was controlled to follow the variations of frequency and phase of the input signal. This technique allowed smooth tracking and extrapolation of the output phase in the event of short periods of signal drop-out by including an effective acceleration memory. Noise pulses or other signal interruptions could result in the loss of signals for a short time during tracking missions. The memory feature allowed the filter to operate through these intervals without losing lock or introducing errors in the data. Output signals from the voltage controlled oscillator were translated down to the audio frequency range in the output mixer. In the model IV filter, this range was 100 cps to 20 kc. The output Doppler signal from the mixer was in phase with the input Doppler signal to the tracking filter because the inherent 90° phase shift in the basic tracking loop was compensated for by the phase-shift networks in the crystal oscillator circuit. The output mixer fed an output a.c. amplifier through a low pass filter which removed modulation products at the output terminals.

In addition to the main tracking phase-lock loop, a closed loop automatic gain control (A.G.C.) section was built into the filter. This included an auxiliary phase detector, d.c. reference signal, d.c. amplifier and i.f. amplifier. The measured amplitude of the auxiliary phase detector was subtracted from the d.c. reference signal and any difference was amplified and applied as bias to the i.f. amplifier.

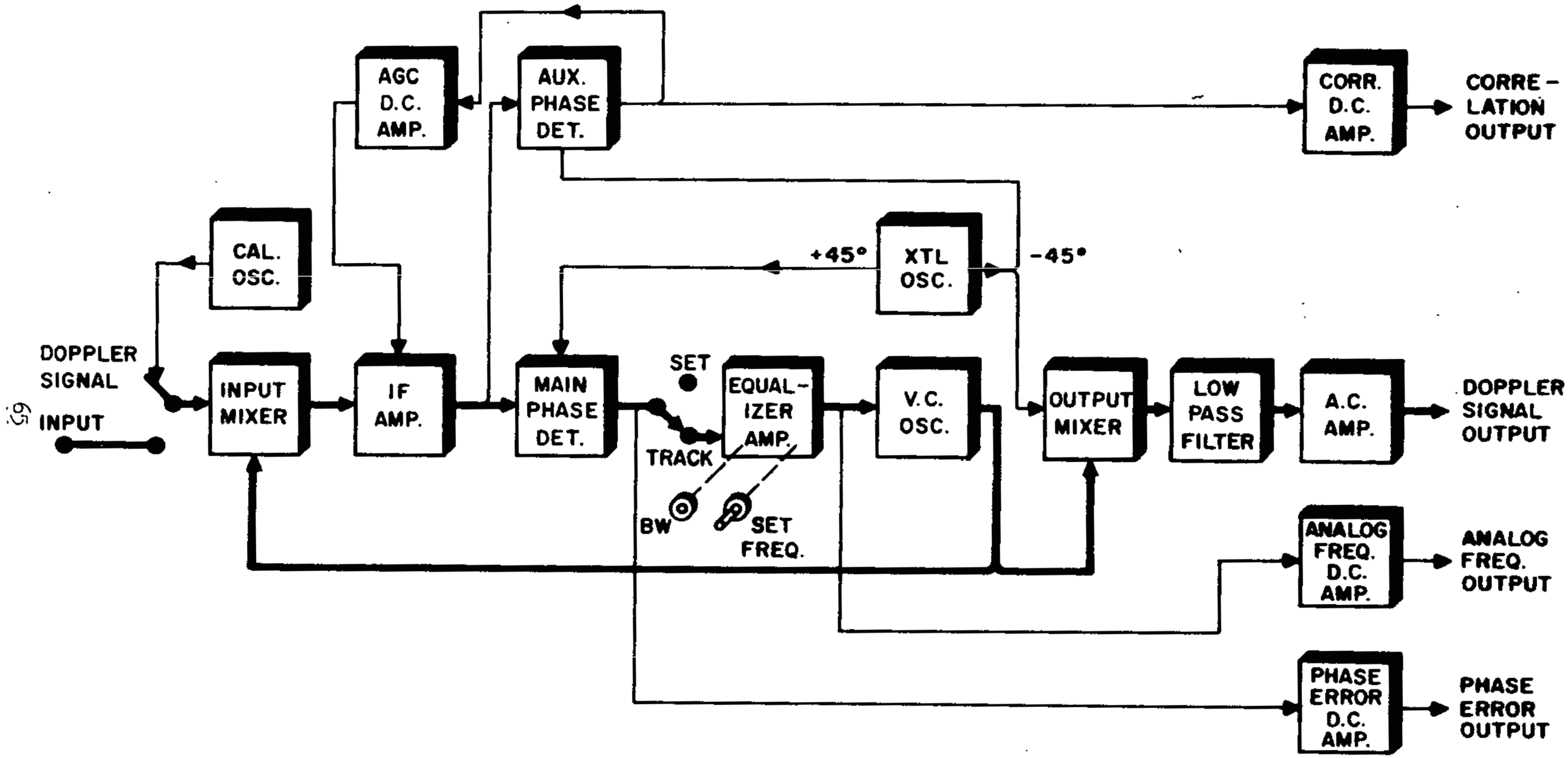


FIGURE 13 BLOCK DIAGRAM OF PHASE-LOCK TRACKING FILTER
INTERSTATE MODEL IV

In addition to the desired filtered Doppler signal, other outputs were made available both to front panel indicating meters and to output terminals. These were the correlation output, the main phase detector output and the analog frequency output. Two factors which were important in the operation and application of the tracking filter were signal-to-noise ratio and signal dynamics.

The signal-to-noise ratio improvement by the tracking filter was that of the ratio of input noise bandwidth to filter bandwidth. Line A of Figure 14 shows the relation of the input noise-to-signal (N/S) ratio in db to the bandwidth for which the output S/N will be unity, when the input bandwidth is 10 kc. The input N/S condition was conveniently expressed in terms of ratios in db above unity N/S since input S/N ratios so much smaller than one are ordinarily used. Figure 14 also shows the measured maximum input N/S to maintain lock-on for filter bandwidth settings between 0.5 and 50 cps. Tests indicated the capability of the tracking filter to lock on to a signal which is buried in noise 6300 to 1 (38 db) when the noise input bandwidth was 16 kc and the filter bandwidth was one cycle per second. For a receiver with a 3-db noise figure, the 38-db value is equivalent to an input power of 2×10^{-20} watts. In terms of receiver performance with commonly used units, this is a sensitivity of -197 dbw or 0.001 microvolts across 50 ohms. This gives a 4-db output S/N, corresponding to about 36° or 0.1 cycle per second rms phase jitter.

The rate of change of received signal frequency due to radial components of velocity, acceleration and rate of change of acceleration defines the signal dynamics. For optimum information reception, the proper bandwidth can be selected to match the signal dynamics as well as the S/N ratio of the signal received. Figure 15 shows the relation of the tracking filter bandwidth to the maximum rate of frequency change and to the equivalent acceleration in g's. Additional technical specifications for the tracking filter are contained in BRL Report No. 1123. Figure 16 is a photograph of the front panel of the tracking filter.

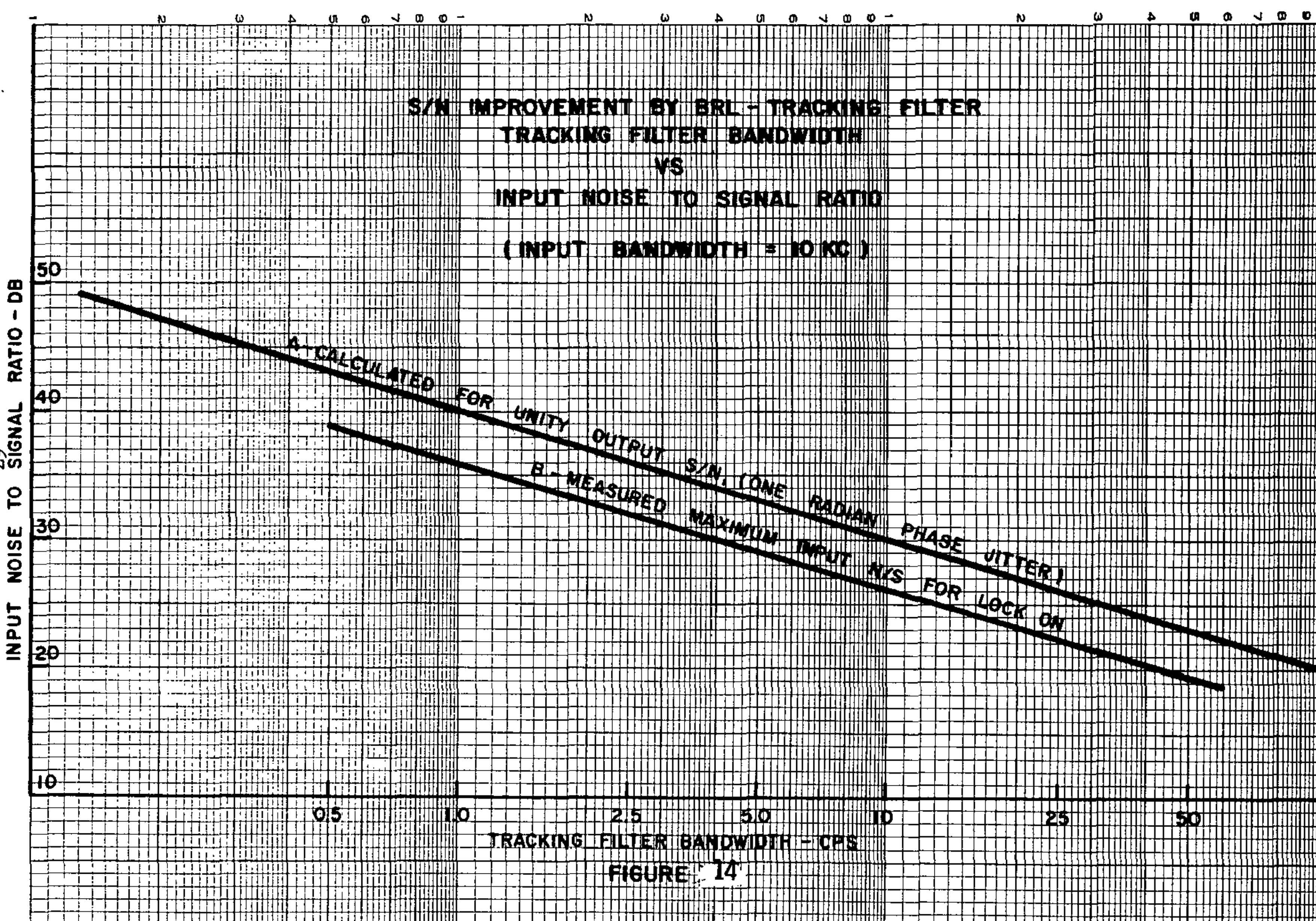

S/N IMPROVEMENT BY BRL - TRACKING FILTER
TRACKING FILTER BANDWIDTH
VS
INPUT NOISE TO SIGNAL RATIO
(INPUT BANDWIDTH = 10 KC)
A - CALCULATED FOR UNITY OUTPUT S/N, (ONE RADIAN PHASE JITTER)
B - MEASURED MAXIMUM INPUT N/S FOR LOCK ON
INPUT NOISE TO SIGNAL RATIO - DB
50
40
30
20
10
0.5
1.0
2.5
5.0
10
25
50
TRACKING FILTER BANDWIDTH - CPS

FIGURE 14

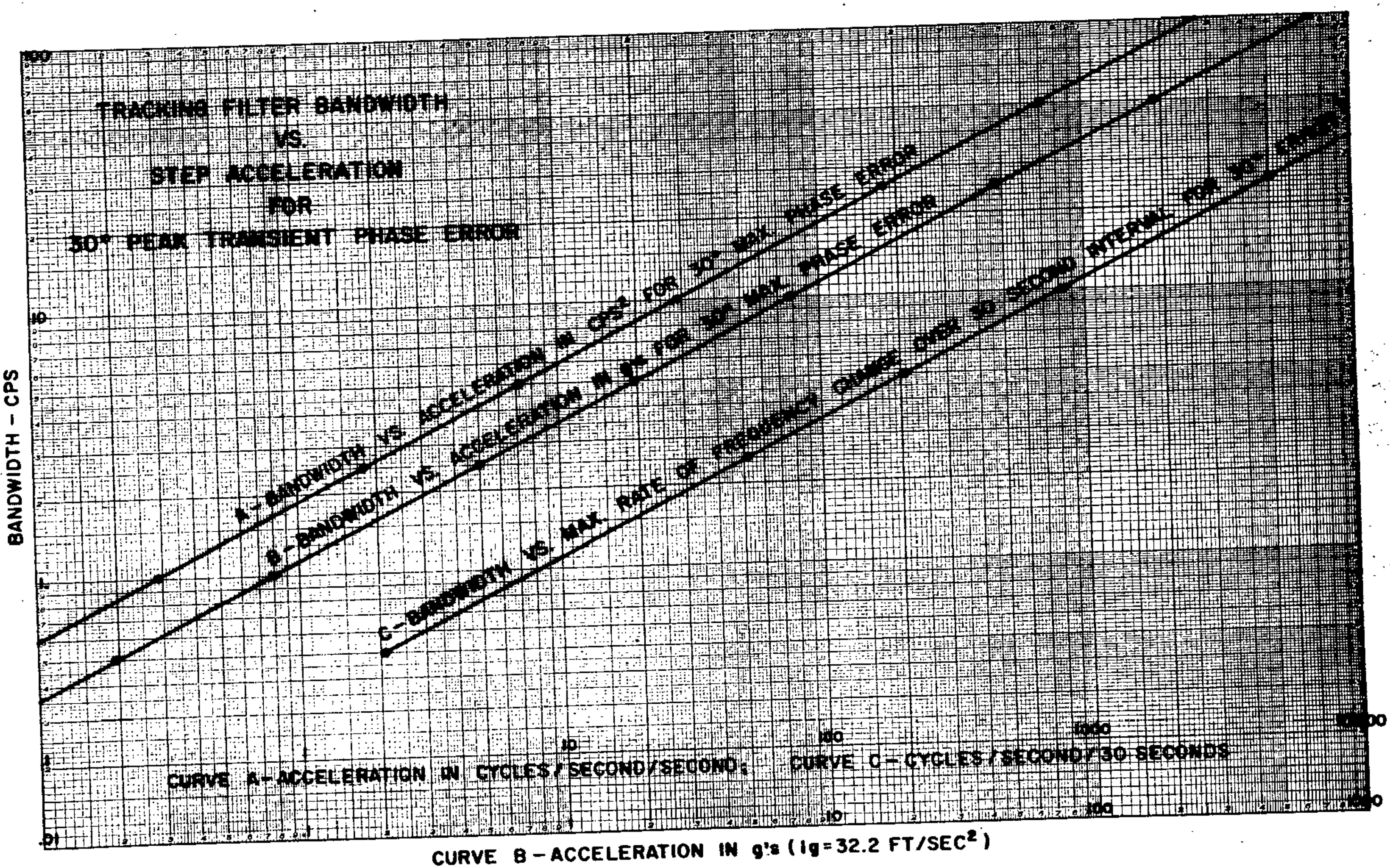

TRACKING FILTER BANDWIDTH
VS.
STEP ACCELERATION
FOR
30° PEAK TRANSIENT PHASE ERROR
A - BANDWIDTH VS. ACCELERATION IN CPS² FOR 30° MAX. PHASE ERROR
B - BANDWIDTH VS. ACCELERATION IN G's FOR 30° MAX. PHASE ERROR
C - BANDWIDTH VS. MAX. RATE OF FREQUENCY CHANGE OVER 30 SECOND INTERVAL FOR 30° ERROR
BANDWIDTH - CPS
CURVE A - ACCELERATION IN CYCLES/SECOND/SECOND; CURVE C - CYCLES/SECOND/30 SECONDS
CURVE B - ACCELERATION IN g's (1g = 32.2 FT/SEC²)

FIGURE 15

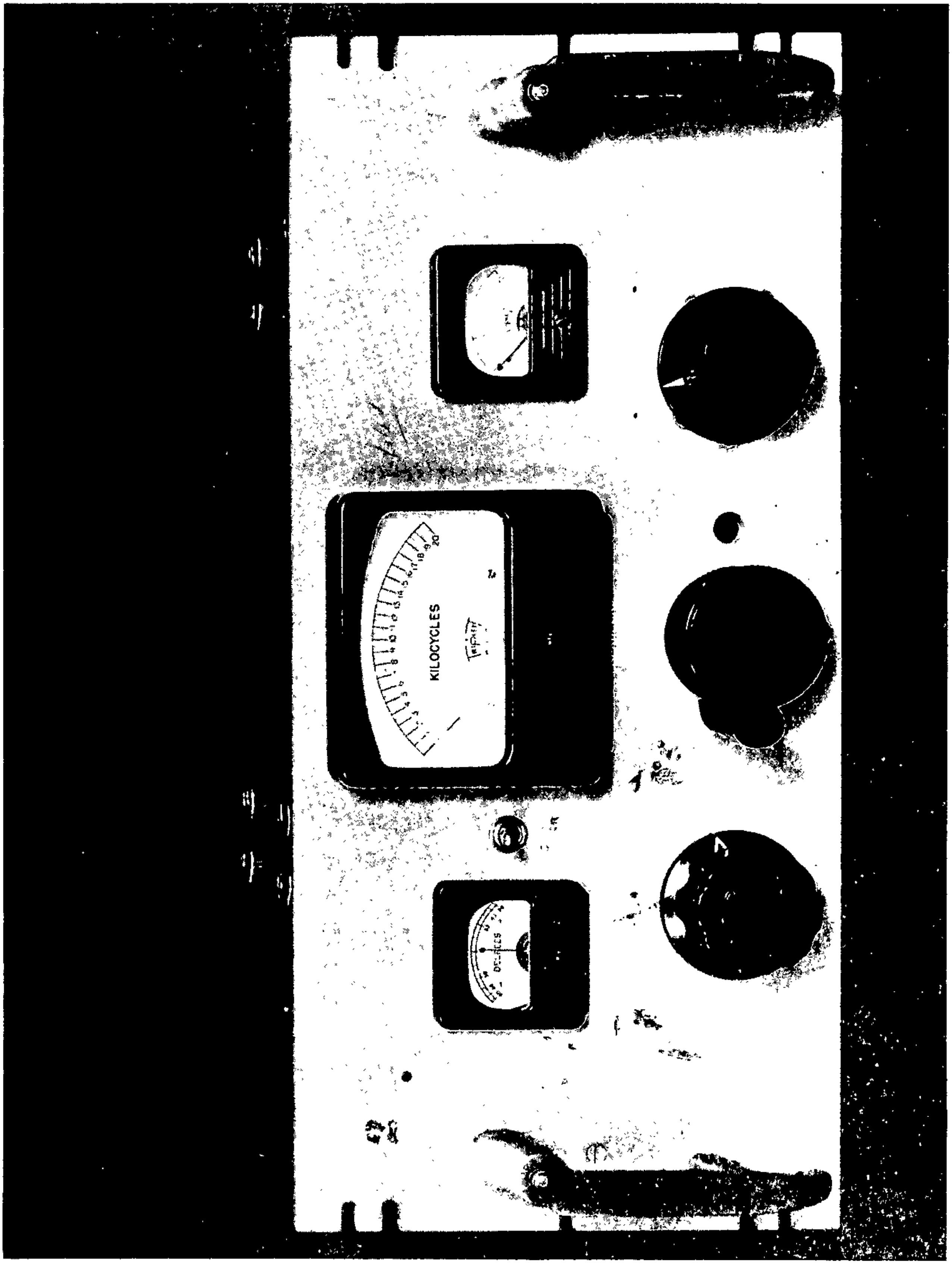


Figure 16 Phase-Lock Tracking Filter

5. Timing. Any system of satellite tracking is dependent upon having both a universal time standard and a local time or frequency standard. For the DOPLOC interim system the National Bureau of Standards standard frequency emissions constituted the standard of time. Local oscillators of the stabilized quartz frequency controlled type served as the ~~local~~ source of frequency.

The local oscillator or frequency standard in each station was a type O-471 manufactured by the Borg Corporation. It had outputs of 100,000 and 1,000,000 cps. This equipment was temperature controlled and kept in constant operation. The basic crystal frequency was actually five megacycles per second. Stand-by batteries were built into the oscillator cabinet and served to supply power over brief periods of power mains failure. Figure 17 is a block diagram of the radio frequency oscillator, O-471(XN-1)/U. Figures 18 a and b are photographs of the frequency standard. This standard provided a frequency which had an instability of less than 1 part in 10^9 over periods of 30 seconds to 1 day.

Various frequencies are derived from the Borg oscillator 100 KC/S output by divider and multiplier circuits. One type of divider circuit is a commercially available Time Code Generator, Model ZA1935 manufactured by Electronic Engineering Company.

This circuit served a dual purpose. It produced outputs of 10 kc, 1 kc, one per second pulses, one per minute pulses and one per 10 minute pulses. In addition to these outputs the unit generated a time code suitable for recording on magnetic tape, and displayed this code on front panel decimal indicators in increments of hours, minutes and seconds. These decimal indicators, appearing as two vertical columns for each unit of time, changed as the code was generated, and the visual display could be pre-set to any desired time in a 24-hour period, allowing the coded time to correspond with the time of day. In most operations it was convenient to set the clock type indicators to Greenwich Mean Time. Figure 19 is a block diagram of the DOPLOC timing system.

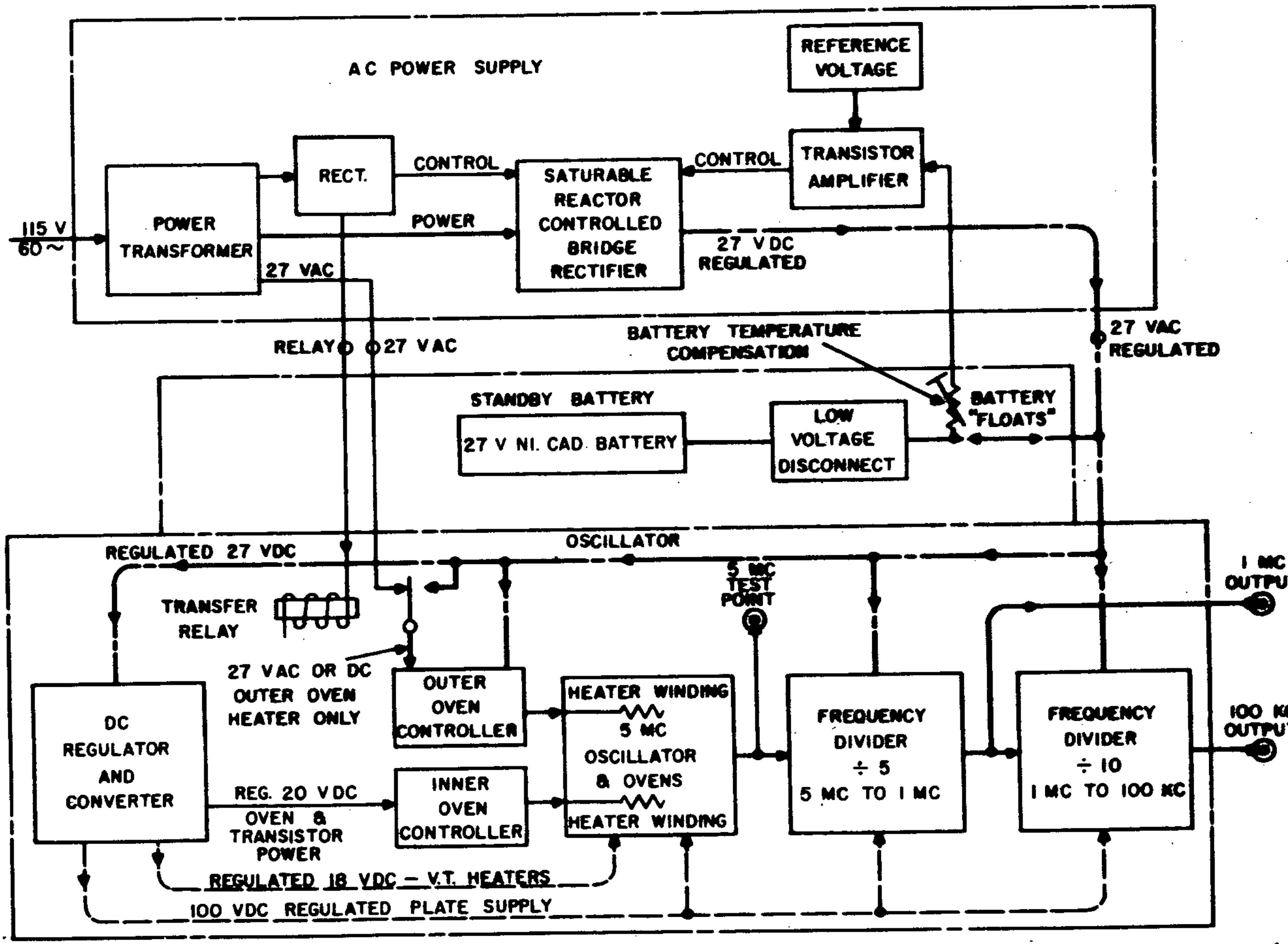


FIGURE 17 RADIO FREQUENCY OSCILLATOR, O-471 (XN-1)/U, BLOCK DIAGRAM

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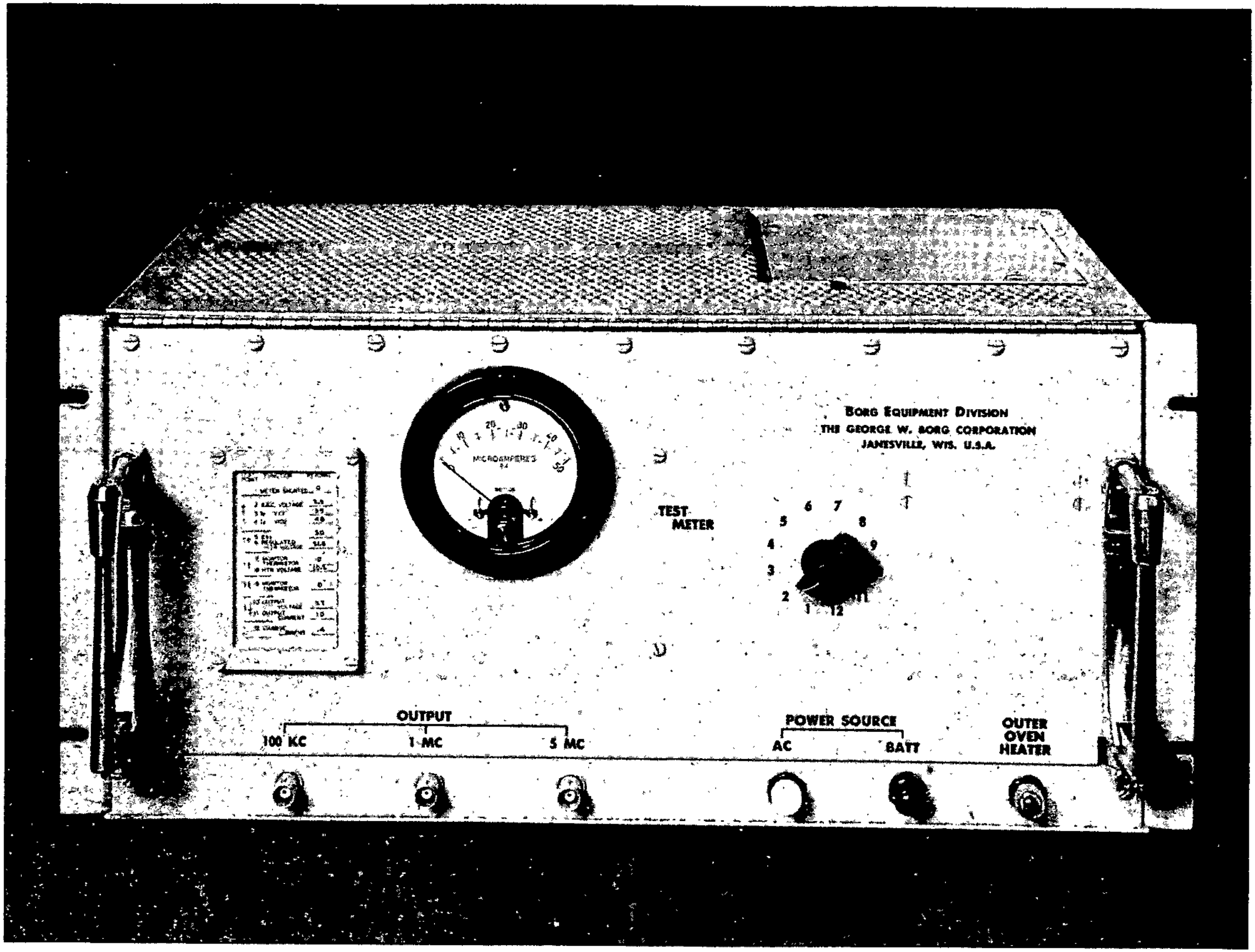


Figure 18a Frequency Standard

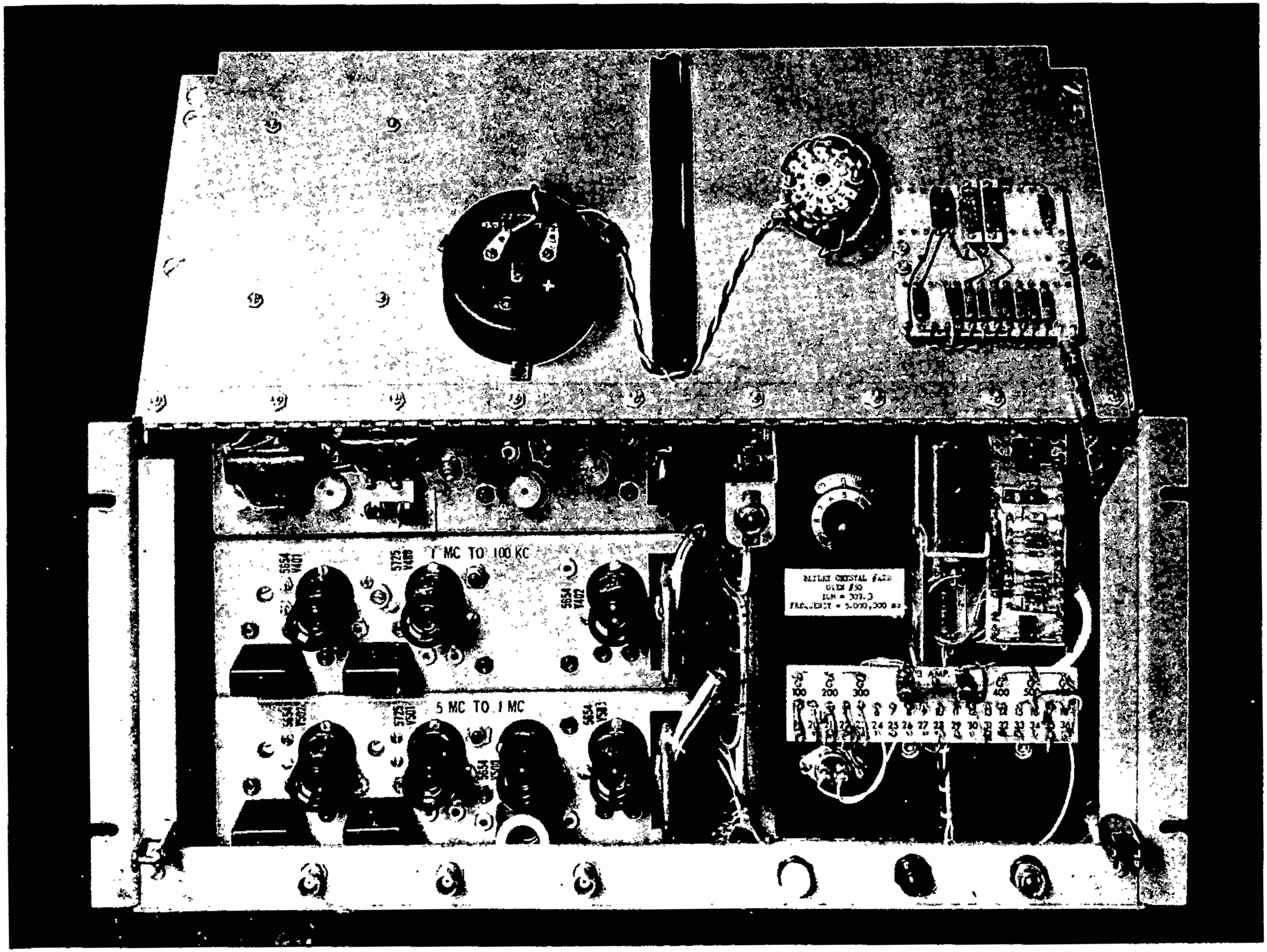


Figure 18b Internal View of Frequency Standard

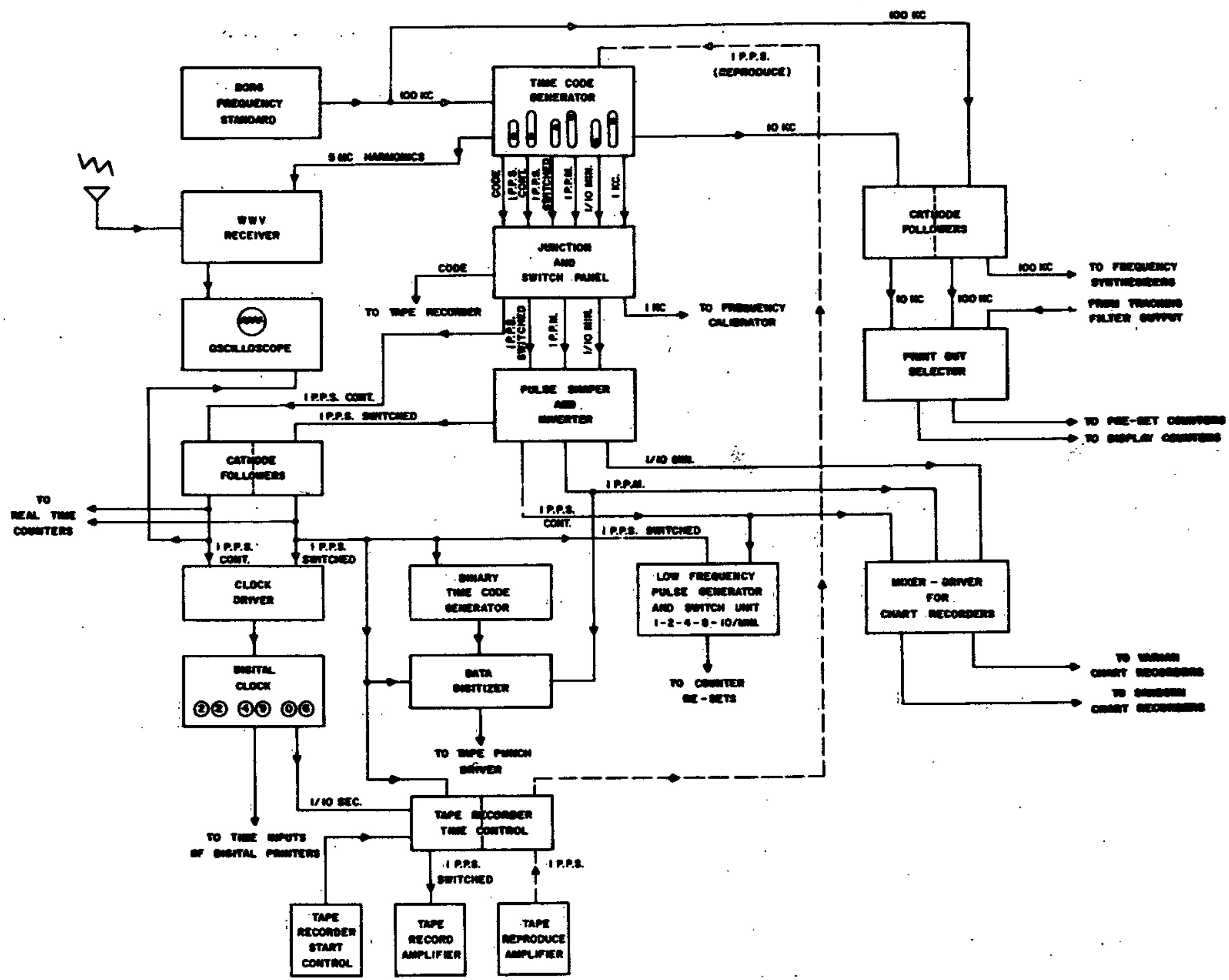


FIGURE 19 BLOCK DIAGRAM OF DOPLOC TIMING SYSTEM

Harmonics of 100 kc and one per second pulse output were used to synchronize the time output with signals received from the National Bureau of Standards station WWV. Provision was made on the rear of the time code generator chassis to couple loosely the harmonics of the basic 100-kc frequency to the antenna of a WWV receiver such as Specific Products Company's type WWVC. This receiver provided several bands for reception of WWV time signals. In this locality 5 mc provided the best signal. Repeated tests conducted over a 24 hour period indicated that the instability in the basic 100-kc frequency was approximately 2 parts in 10^8.

Since the one-per-second output from the time code generator could be shifted in small time increments, this signal could be accurately synchronized with the one per second tone bursts from WWV. This WWV signal was displayed on the vertical axis of a monitor scope whose horizontal sweep was triggered from the station-generated one-per-second pulse. Proper manipulation of either the "Advance" or "Retard" button enabled the operator to establish coincidence of the start of the tone burst with the start of the scope sweep to an accuracy of one millisecond. Sychronization of the station's timing system occurred at least once each day and was always checked just prior to each tracking operation. Clock time of day was encoded on the basis of a 24-hour clock with six code groups necessary to display a 24-hour interval. The code was generated in a 4-2-2-1 binary coded decimal form, with each time indication identified by a 20-digit code. The output was a 100-cycle carrier, modulated at a 25-pulse-per-second rate, upon which a 1000-cycle signal was superimposed. Although not used for search purposes, the code was suitable for magnetic tape search.

Figure 20 indicates how the outputs derived from the time code generator circuit were distributed via switch circuits and cathode followers to the various timing and control circuits required in the system. Standard pulse shapers and inverters produced the desired polarity, duration, and amplitude of signals for the timing applications.

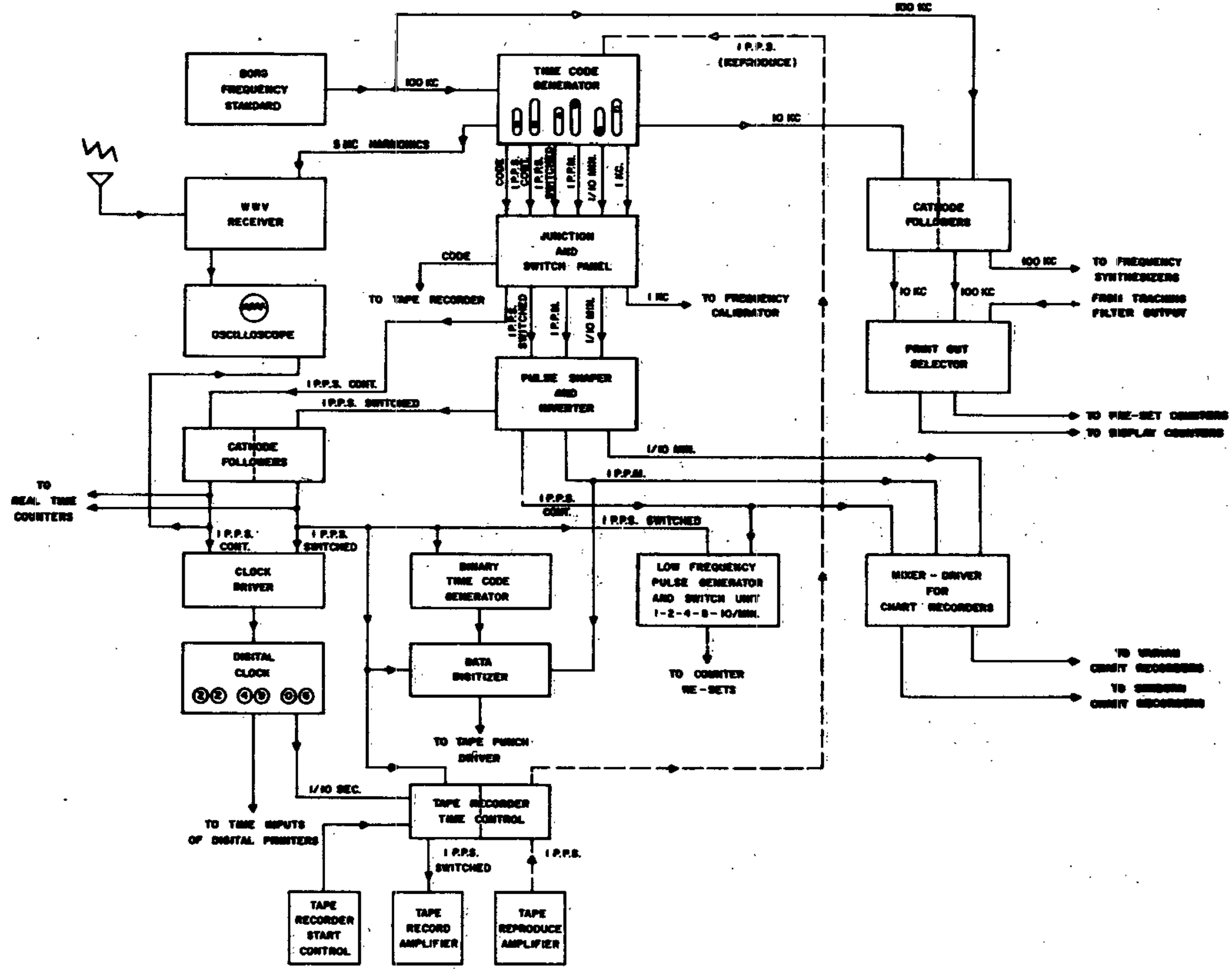


Figure 20 Block Diagram of DOPLOC Timing System

Timing marks were produced on one edge of the strip-chart record on both the Varian and Sanborn recorders at the rates of one per second and one per minute. In addition, one-per-ten second markers could be superimposed directly on the data trace of the Varian recorder. The 1000-cycle output of the time code generator was used to produce calibration frequencies in 3 kc steps over the range of 3 to 15 kc for calibrating the Varian recorders.

By front panel switching for each of four recording channels, a print-out selector circuit allowed proper data and timing inputs to be switched to the pre-set and display counters for either period or frequency measurements. A low frequency pulse generator operating from the one-per-second input also allowed switching the print rate of the digital recorders from one-per-second to once per 2, 4, 8 or 10 seconds.

The digital clock and the real time counters were driven from the basic one-per-second pulse derived from the time code generator. The real time counters operated in a manner similar to that of the decade counters in the time code generator described above. Time was advanced in one-per-second increments and displayed in hours, minutes and seconds, with the outputs being a discrete voltage level for each digit displayed. A Hewlett Packard type 560A digital printer was used to print out this information. The digital clock also advanced in one-second increments, and time was displayed in hours, minutes and seconds with the output in the form of contact relay closures for each digit indication. Modification of the 560A digital printer was necessary before it would accept these data. The data digitizing also required time indications and these were produced in a binary time code generator by counting the one-per-second time pulses in a straight binary form and displaying the output with front panel indicators. Command pulses, generated external to the data digitizer and synchronized to the time pulses, shifted the time data out of the code generator into the data digitizer for read-out.

A tape recorder time control circuit was used to begin time pulse recording at a one-per-second rate to the nearest ten-second real time indication. This time was manually recorded and served as a known start time for setting up indications for play-back of tape recorded data. The recorded one-per-second pulses were then used as the timing source for all play-back requirements.

6. Data Recording Equipment. The basic Doppler information, available at the output of the phase-locked tracking filter, was a constant amplitude, varying frequency sine wave. Other data available from the filter were the correlation signal, the phase error output, analog frequency in terms of a d.c. voltage and the automatic gain control voltage. Recording was accomplished in both analog and digital form utilizing magnetic tape recorders, strip chart recorders, digital printers and paper tape punches. Figure 21 is a block diagram of the recording section used in the DOPLOC receiving stations. Each type of recording is briefly described in the following:

a. Digital Print Out. Pre-set counters and display counters provided readings of either period or frequency of the tracking signal from the output of the tracking filter. The type of recording utilized, period or frequency, was determined by the required accuracy of a specific tracking operation. When frequency output was desired, a known number of cycles of the external timing frequency obtained from the precision frequency standard, was counted by a pre-set counter after proper setting of the multiplier dials. A start pulse derived at the beginning of this count and a stop pulse derived at the end of the count, were used as gate controls for a second counter called the display counter. The signal of unknown frequency was fed to the gate of the display counter, where it was gated by the control gate pulses, to the counter decades for counting and displaying. For example if a 10-kc time base was used and the multiplier dials of the pre-set counter were set to read 10,000 then the gate would be open for one second, and a 5-kc frequency would be directly read out as the number 5000.

When period output was desired, the signal frequency was fed to the input of the pre-set counter, and the multiplier dials were set to count the desired number of cycles of this frequency. The display counter then

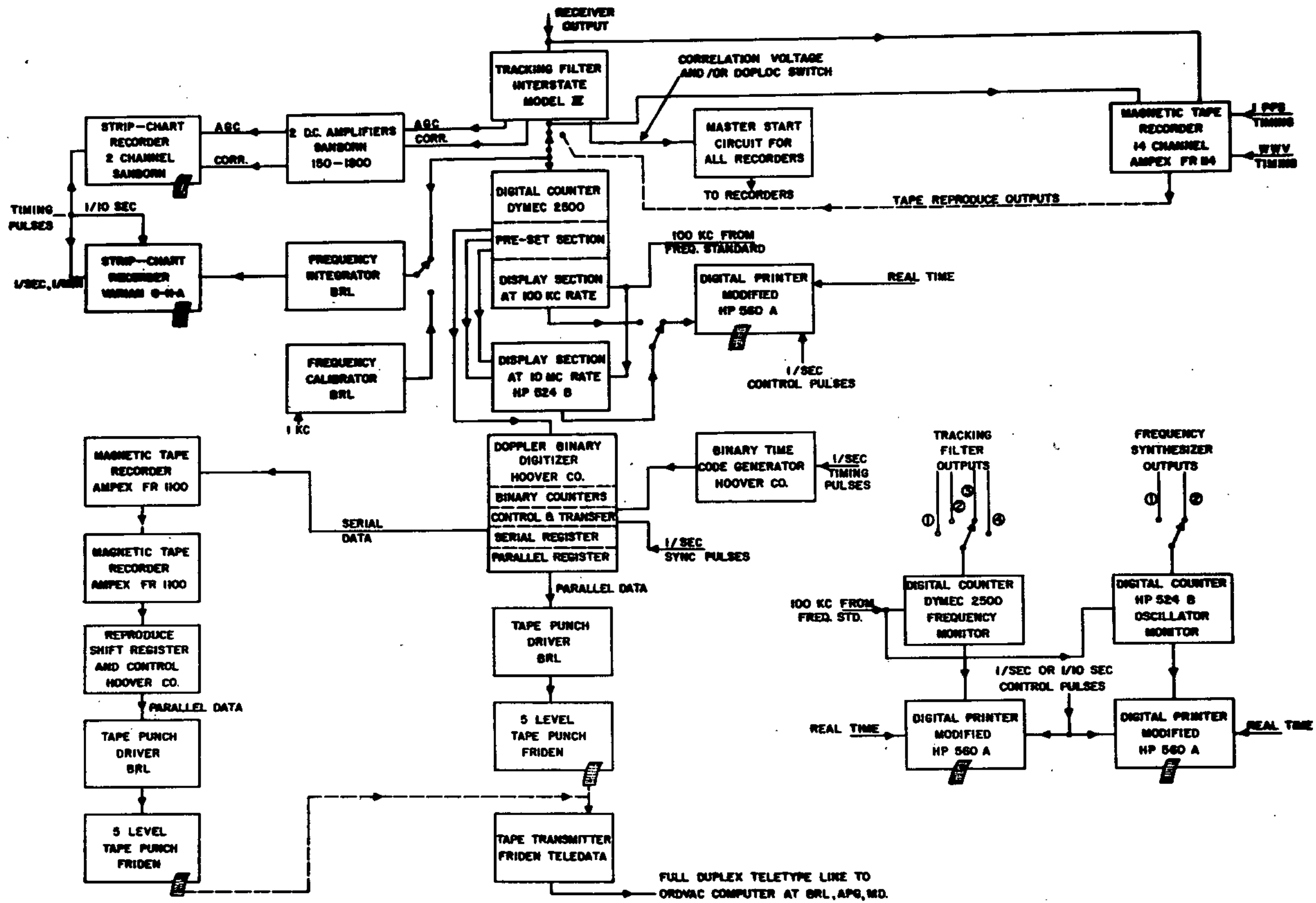


FIGURE 21 BLOCK DIAGRAM OF DOPPLER DATA RECORDING SYSTEM FOR A SINGLE CHANNEL

counted the timing pulses for the interval of a known number of cycles of the signal frequency and displayed the count. For example, assuming the Doppler frequency to be 2 kc/s, the multiplier dials of the pre-set counter might be set to 1000 to allow the display counter gate to be open for one half second. If the timing frequency were 100 kc/s, the display counter would read the number of pulses in one half second or 50,000 counts. This thus produced a period measurement which is the inverse of the previously described frequency measurement.

The period measurement obviously provided the highest accuracy. For improved accuracy of measurement a 10-mc counter was used to obtain the period count. The recorded data were printed out on the Hewlett Packard model 560A printer. This printer operated with counters using the binary decimal counting system and produced a specific voltage level for each displayed number. This voltage level was fed to the corresponding digital place in the printer which sensed the voltage and printed the number displayed on the counter. The printer accepted data entered in parallel and all columns were printed simultaneously on command. The capacity of the printer was eleven digital places. For frequency, or lower resolution period measurements, the first five digits were used for the Doppler data, and the last six were for time indication. For period measurements of higher resolution, using the 10-mc counter, the first seven digits were used for the Doppler data, and the remaining four for time indications.

The time data presented to the appropriate print wheels could be one of two kinds, depending on the circuitry used to generate them. If the data were generated from modified counter decades with a specific voltage level produced for each decimal number in the decade, then no internal modification of the printer was required. However this required a separate real time counter for each digital printer used. If several channels of data were being printed, the equivalent number of real time counters required became cumbersome and difficult to synchronize with WWV time signals.

The second kind of real time data was generated from a digital clock, Chrono-log model 2600-4, the output of which was in relay contact closures. Modifications to the digital printer were required for those positions where

time was recorded. The advantages of using this clock were the ease of setting up the real time information each day, the ease of synchronization with WWV time signals and the fact that one clock could drive many printers. All of the printed time data were identical and properly correlated. The disadvantage was the modification of the printer to accept the time information from the digital clock. The printer became a hybrid instrument with part of the print wheels operating from voltage levels and part from contact closures. Once the modification had been made the reliability and ease of operation were greatly improved.

b. Strip Chart Recorders. Two types of strip chart recorders were also used to record the output of the tracking filter. The first was a single channel Varian recorder, model G-11-A, utilizing a five inch wide recording paper. Timing marks were placed on the edge of the paper by an independent stylus and also superimposed on the data stylus. The Doppler data were fed to an integrator where the frequency was converted to a d.c. voltage signal. Frequent frequency versus deflection calibrations were made.

The automatic gain control and correlation outputs of the tracking filter were recorded on a two-channel Sanborn model 152-100B, normally at 1 mm per second chart speed. Timing marks were recorded on the edge of the paper. Calibrations were applied after a satellite pass.

c. Magnetic Tape Recording. Since provision was made for handling only one channel of data through the real time encoder for transmission over the teletype line to the computer, some provision had to be made for storing the data from the other three channels. Back up data were also desirable in case of other equipment failure or errors in data transmission. Therefore, all data from the tracking filters were recorded on magnetic tape. An Ampex FR-114 fourteen-channel recorder utilizing one-inch tape was used at each receiving station. Tape speeds from 1 7/8 inches per second to 60 inches per second were available. On most tracking operations tape recordings were made of receiver output, tracking filter output, station timing signals and WWV time signals. Spare channels were then available for recording any other data desired. In the reproduce mode four channels were available for simultaneous playback of any four of the switch selected fourteen channels of data.

An Ampex model FR-1100 magnetic tape recorder, using 1/2" tape, and recording at speeds of 3 3/4 to 30 inches per second was used to record the binary output data in digital form at the output of the serial shift register.

d. Doppler Data Digitizer. To permit rapid data handling and real time transmission back to the computer it was necessary to digitize and encode the Doppler data at the stations. Two basic functions of the digitization system were to produce in binary form real time data at the beginning of each recorded output and period data of the Doppler signal. The first function was accomplished by the binary time code generator at each tracking station and the second by the Doppler Data Digitizer (DDD) for each recording channel in the station. Standard transistorized building block logic was used in both equipments. The DDD was built to BRL specifications by the Hoover Electronics Company of Baltimore, Maryland. This equipment is described in detail in BRL Report No. 1123 by C. L. Adams. Figure 22 is a block diagram of a single channel Doppler Data Digitizer. Figure 23 is a simplified block diagram of the interim DOPLOC Data handling System. Figure 24 is a photograph of the data Digitizer. The digitizer operated a tape punch driver which in turn operated a Friden paper punch Model 2 to produce the binary data in the proper format.

e. Data Format. The punched-paper-tape type of output data were produced in straight binary form because of the input requirement of the BRL ORDVAC computer used in the calculation of the satellite orbital parameters. Each recording channel in the station produced data in standard five level teletype tape in the format shown in Figure 25.

A complete data block, or word, was contained in seven rows of the five-channel tape with time and Doppler data in six rows of the first three channels. At the beginning of each word, in parallel with the binary data in row one, a block or time marker bit was produced in channel four. This occurred at a one-per-second rate and was correlated with the digital printer readout signal. Modification in the digitizer circuits was made to allow a one-per-minute bit to be punched in row two of channel four to further correlate timing data. An end of word marker, acting as a computer control, was produced in all five channels of row seven.

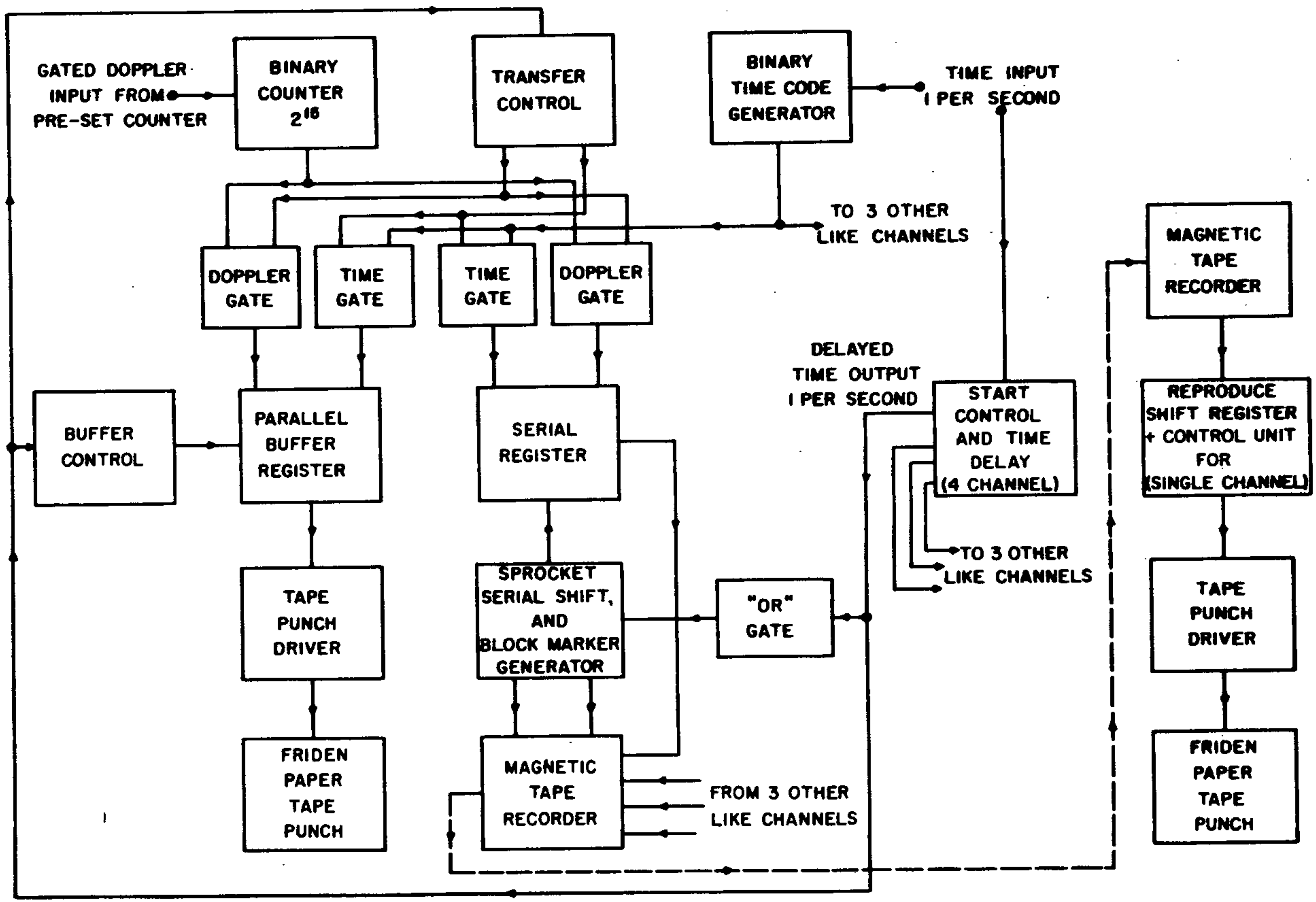
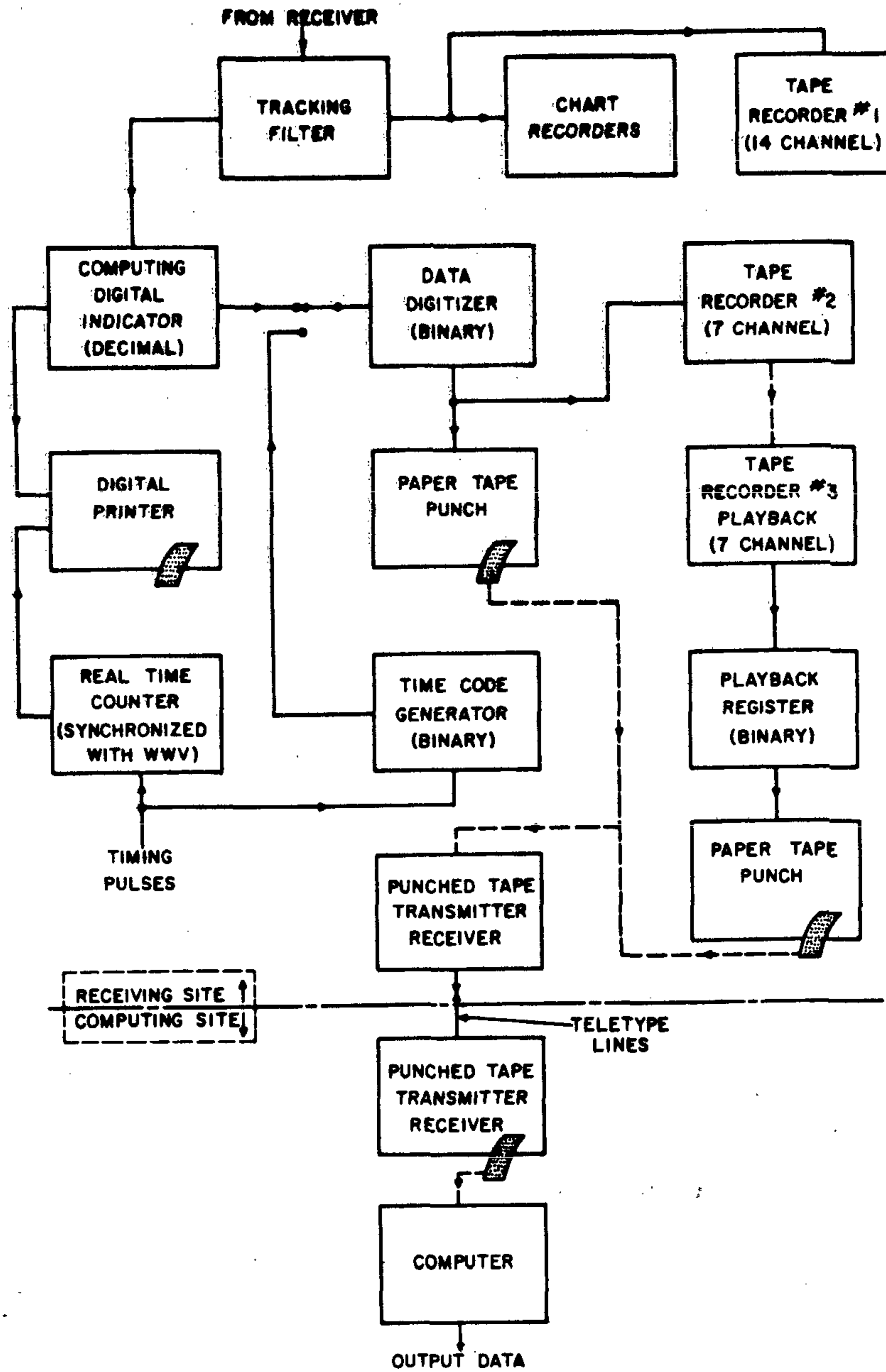


FIGURE 22 BLOCK DIAGRAM OF SINGLE CHANNEL DOPPLER DATA DIGITIZER



SIMPLIFIED BLOCK DIAGRAM — DOPLOC SYSTEM DATA HANDLING
FIGURE 23

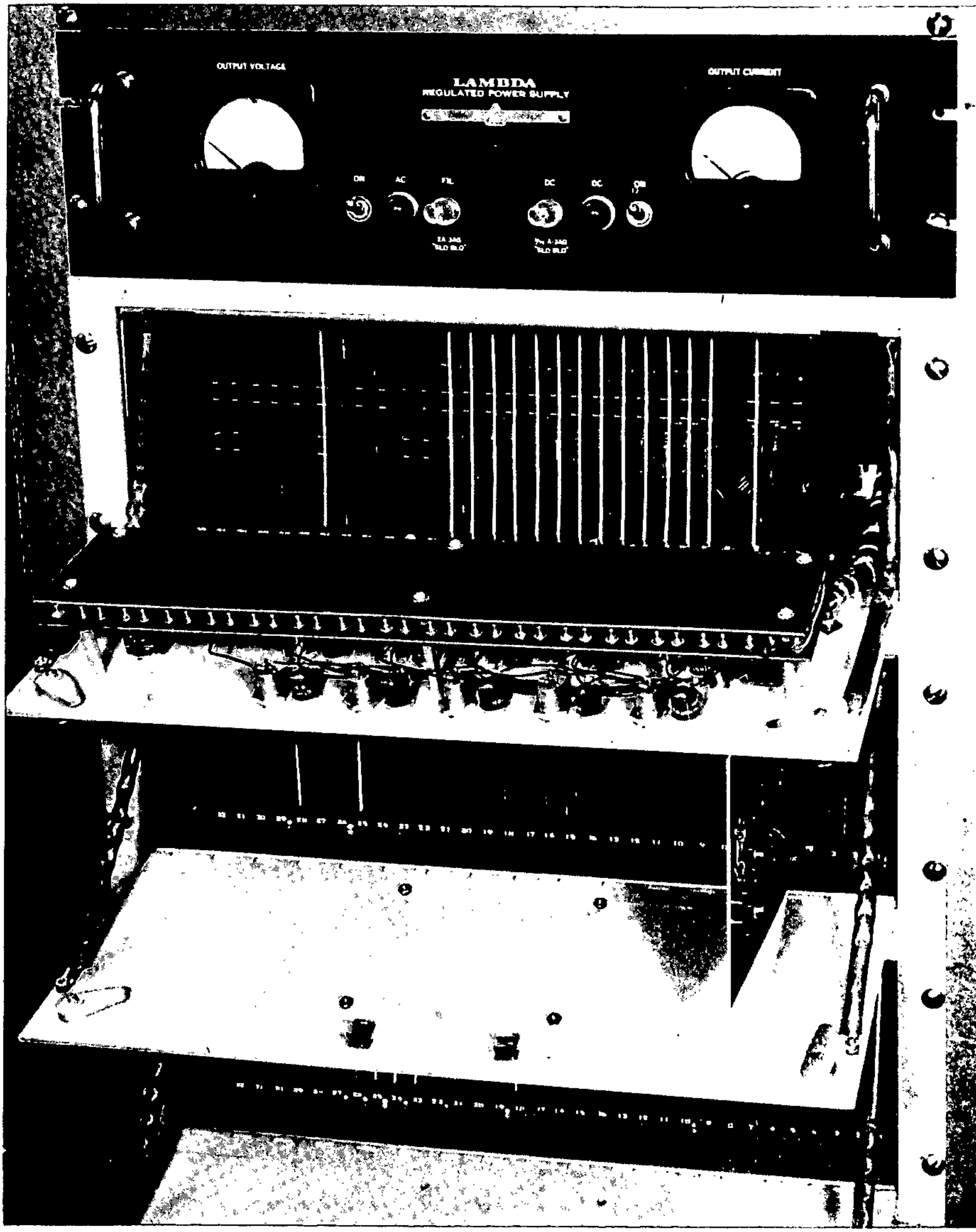
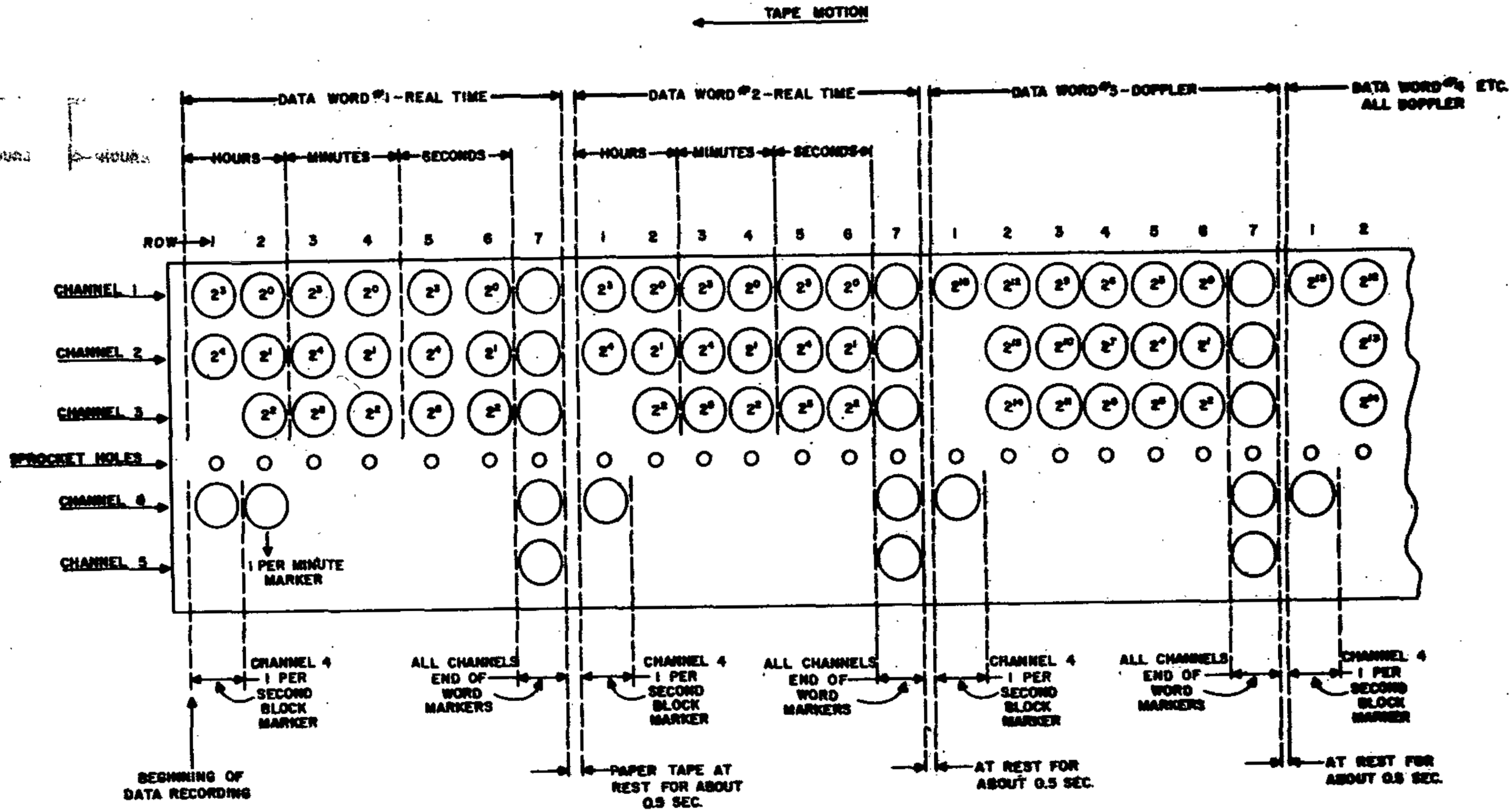


Figure 24 Data Digitizing Equipment



NOTES:

1.-PUNCH RATE IS APPROXIMATELY 20 ROWS PER SECOND OR 50 MILLISECONDS PER ROW.
2.-MAXIMUM TIME FOR ONE DATA WORD IS 0.5 SECONDS.
3.-EACH DATA WORD IS RECORDED AT A RATE OF ONE PER SECOND.
4.-THE TAPE IS AT REST BETWEEN DATA WORDS FOR APPROXIMATELY 0.5 SECONDS.

FIGURE 25 PUNCHED PAPER TAPE FORMAT – DOPLOC STATION

Manual operation of a start switch at the console, or automatic start switching from the automatic lock-on circuits when the tracking filter locks on a received signal, began the tape punching sequence. The first data word contained universal time data and all subsequent blocks contained Doppler data. The data were punched in parallel, one row at a time at a rate of 60 milliseconds per row. After each end of row marker in row seven, the tape was at rest for approximately 0.5 second while the counting process in the digitizer took place. The one-per-second timing signal triggered the readout system and the count just accumulated was punched out.

f. Data Transmission. A very important part of any satellite tracking net is the data transmission equipment. If data are to be transmitted in real time and orbits computed in minutes after a satellite pass, the transmission system must be reasonably fast, accurate and dependable. In designing the DOPLOC interim equipment it was determined that satisfactory transmission could be obtained using a 60-word-per-minute commercial telegraph channel, if connected to terminal equipment that contained a system of parity checking of transmitted data. A commercial paper tape transmitter receiver called Teledata, manufactured by Friden, Incorporated, was chosen. The model 7-B Teledata shown in Figure 26 was used with five channel tape and consisted of a reader-punch chassis and a transmitter receiver chassis. One Teledata unit was required at each field station location and one for each station's output at the computer location, connected by a full duplex telegraph line. This type of connection allowed simultaneous transmission in both directions.

Any type of five bit code read from the transmitting tape was transmitted as a seven bit code by adding a redundant bit to each of two groups of the five tape code bits to form two parity groups, one group containing four bits and the other group containing three bits. The sequential transmission cycle was so arranged that bits were sent alternately from the two parity groups. The received code was checked for accuracy in the tape punch section by independently checking of each group of bits. Operation of an even number of punch pins in either group was registered as an error.

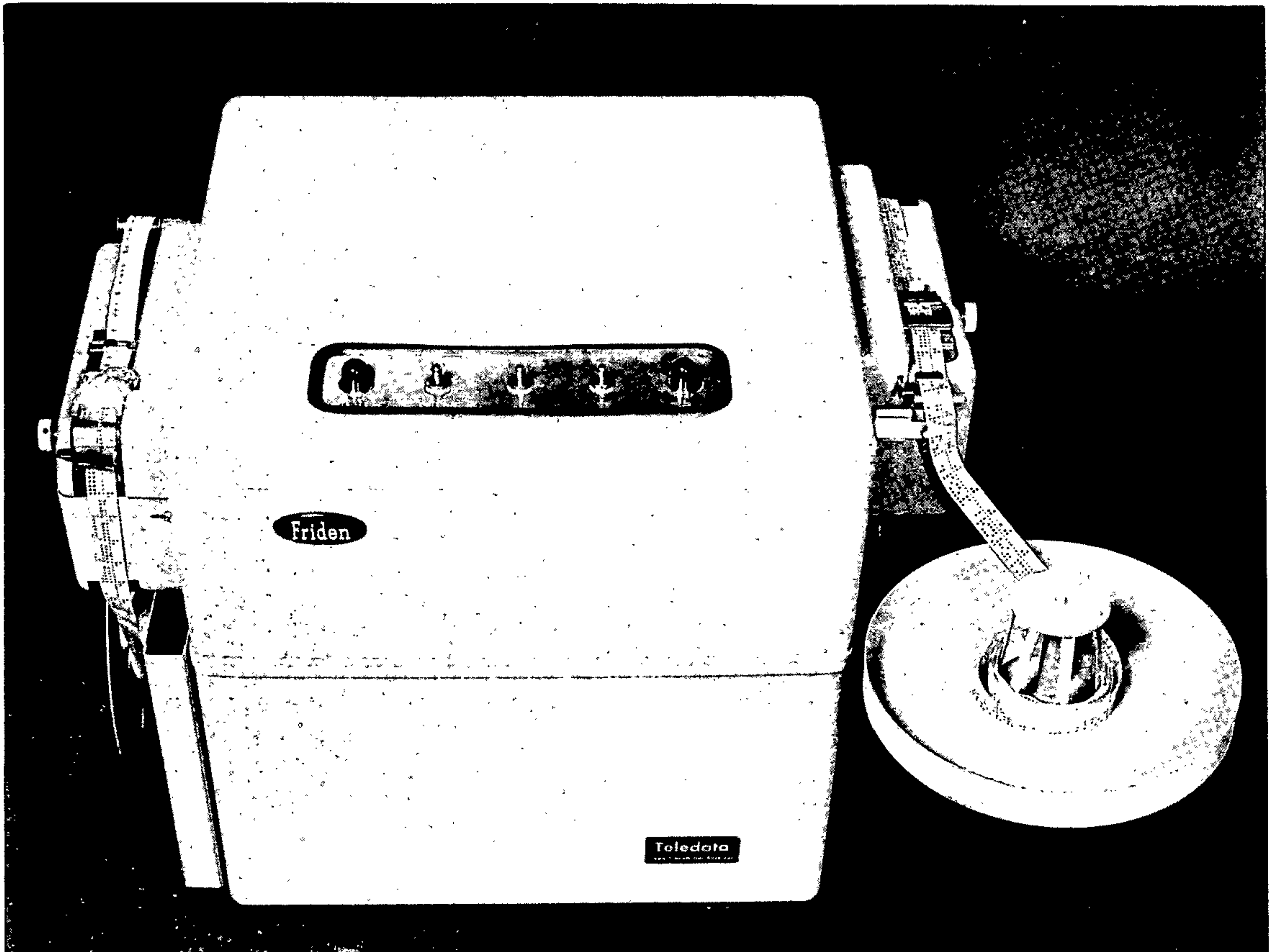


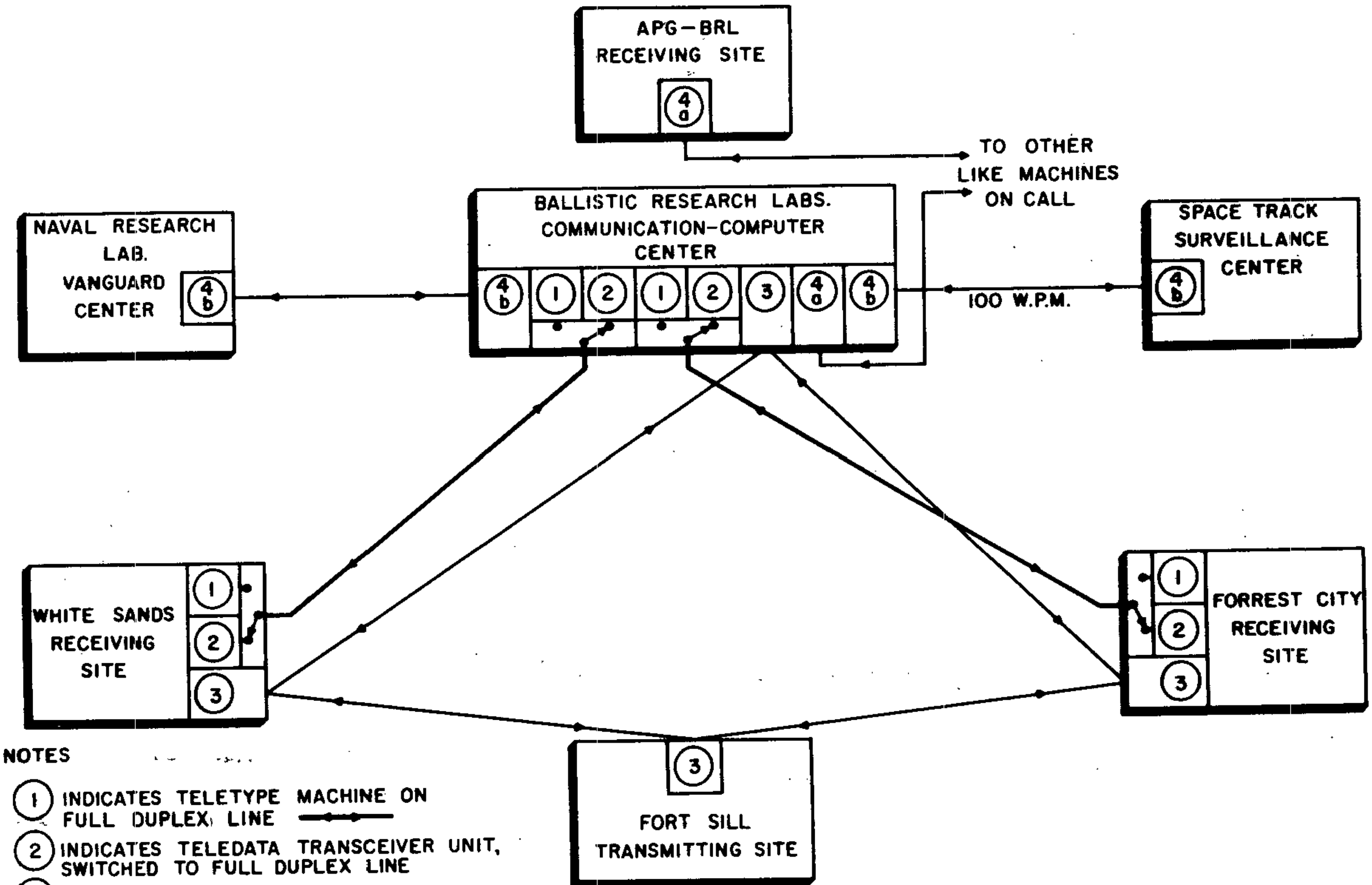
Figure 26 Trledata Transmitter - Receiver Unit

The pins associated with the redundant bits do not punch the tape so that the received tape was in the identical five channel form as the transmitted tape.

In order to utilize the full capabilities of the full duplex line, provision was made to switch the lines at the ends of the links from the Teledata to commercial teletype machines, thereby providing simultaneous two-way teletype communication during periods when the data tapes were not being transmitted. In addition to this combination communication-data link between the receiving stations and the BRL computer, a standard half duplex teletype link tied all stations together in parallel. A separate 100-word-per-minute teletype line linked the Laboratories' computing center with the National Space Surveillance Control Center, Spacetrack, New Bedford, Massachusetts.

During the Vanguard project, another half-duplex teletype link existed between the computer center and the Naval Research Laboratory in Washington D. C. The tracking station at APG and the BRL computing center each had a commercial half-duplex teletype machine which could be connected on call to other similar machines throughout the nation. It was necessary to operate with this variety of communication equipment because of the large number of agencies involved in launching the various types of satellites and probes which were to be tracked. Figure 27 shows the data transmission and communication network.

A series of tests were run on the data links to determine the accuracy of data transmission. Both Teledata and teletype equipments were adjusted to optimum performance and a punched tape with a known code format containing 4000 data bits was transmitted from BRL to each receiving station. Then, over a period of several days, this test tape was transmitted back to BRL from the stations at selected times. A statistical record was made of errors. The same tape was transmitted over the links without the Teledata parity check. This resulted in roughly twice as many errors as were made by the Teledata machine. The teletype equipment also showed no indication that an error had been made. With the Teledata equipment, an



NOTES

(1) INDICATES TELETYPE MACHINE ON FULL DUPLEX LINE

(2) INDICATES TELEDATA TRANSCEIVER UNIT, SWITCHED TO FULL DUPLEX LINE

(3) INDICATES MULTI-POINT TELETYPE MACHINE ON HALF DUPLEX LINE

(4a) INDICATES ON-CALL TELETYPE MACHINE

(4b) INDICATES FULL-TIME LEASE TELETYPE MACHINE

ALL LINES AND MACHINES ARE FOR 60 W.P.M. TRANSMISSION, EXCEPT AS NOTED.

FIGURE 27 DOPLOC DATA TRANSMISSION — COMMUNICATION NETWORK

error caused the machine to stop transmitting and thus permitted error location and correction. Data transmitted over a 2000-mile link using 60-word-per-minute telegraph lines showed an error rate of only one part in 60,000. This was quite adequate for the interim DOPLOC system data handling requirements. A more rapid rate of data handling was planned for the final equipment.

g. Data Transmission Accuracy Tests. An analysis of data received from tracking both active and passive satellites showed an occasional RMS scatter of as much as three cycles per second. This resulted in some suspicion of the performance of the phase-locked tracking filter. A series of tests were made at the Laboratories' tracking station on data simulating those obtained on actual satellite passes. The test results showed a random scatter in the data corresponding as closely as could be determined to the precision of measurement, thus removing the suspicion from the tracking filter. The random scatter was thus attributed largely to propagation phenomena. The satellite spin and instability of the satellite transmitter in active satellites will introduce a limited amount of data scatter also. Efforts to analyze the data for systematic errors as well as random errors resulted in an increase in the precision of the period measurements by using a ten megacycle counting rate instead of the one hundred kc rate. After an extended series of tests using simulated data mixed with noise and various tracking filter bandwidths it was determined that the peak frequency scatter was 0.16 cycles per second and the rms frequency error was 0.052 cycles per second. Figure 28 is a block diagram of the equipment used for the frequency measurement tests.

h. Data Samples. Examples of the types of recorded data are shown in Figures 29 - 34. Figure 29 is a dual channel, strip chart record of data obtained on pass 140 of satellite 1960 Delta (Discoverer XI) at the Forrest City, Arkansas, station. Operation was in the passive mode. The upper record of the chart indicates frequency as a function of time and shows three distinct segments of received Doppler frequency. These segments correspond to the times of passage of the satellite through the beams

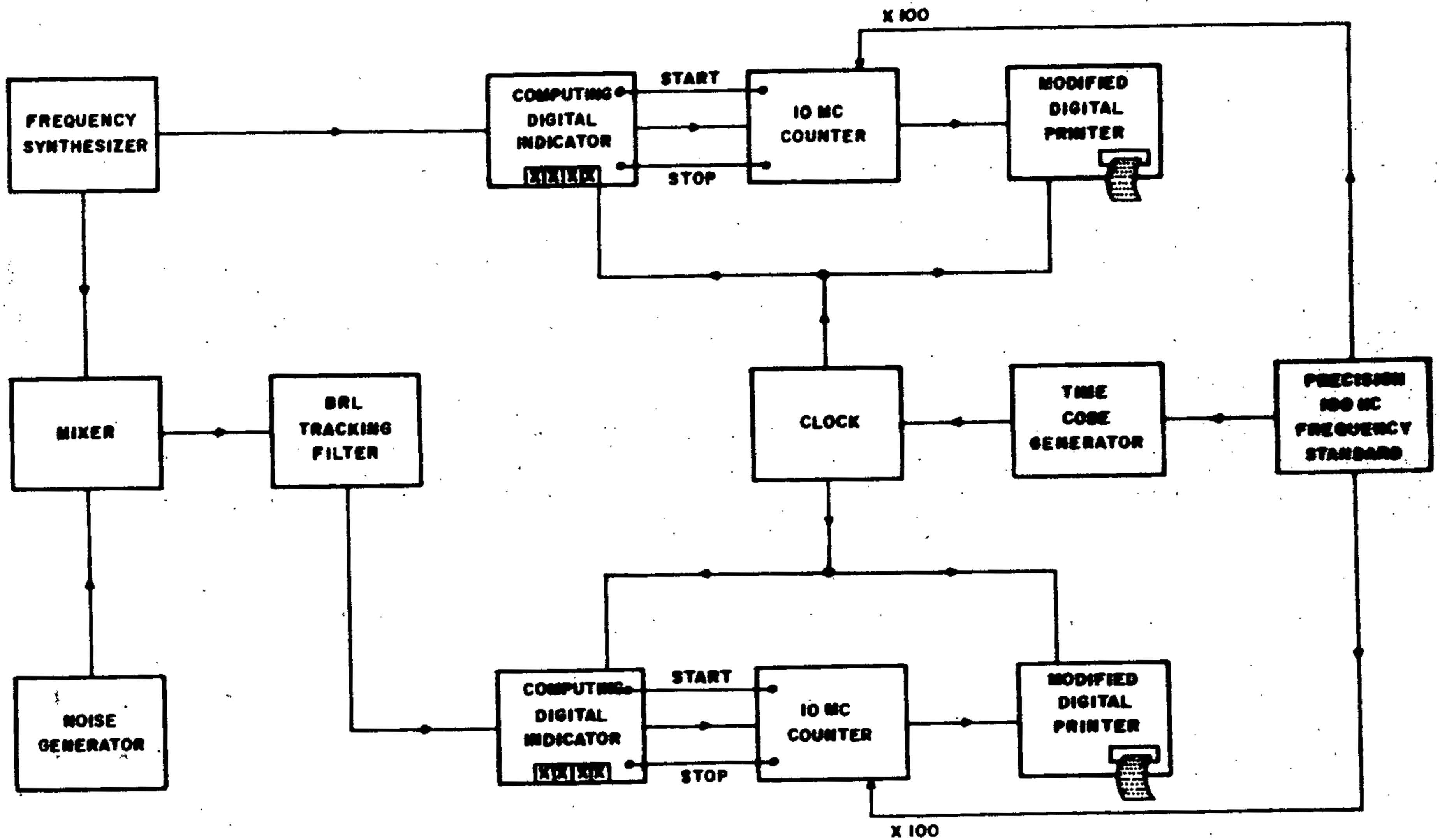
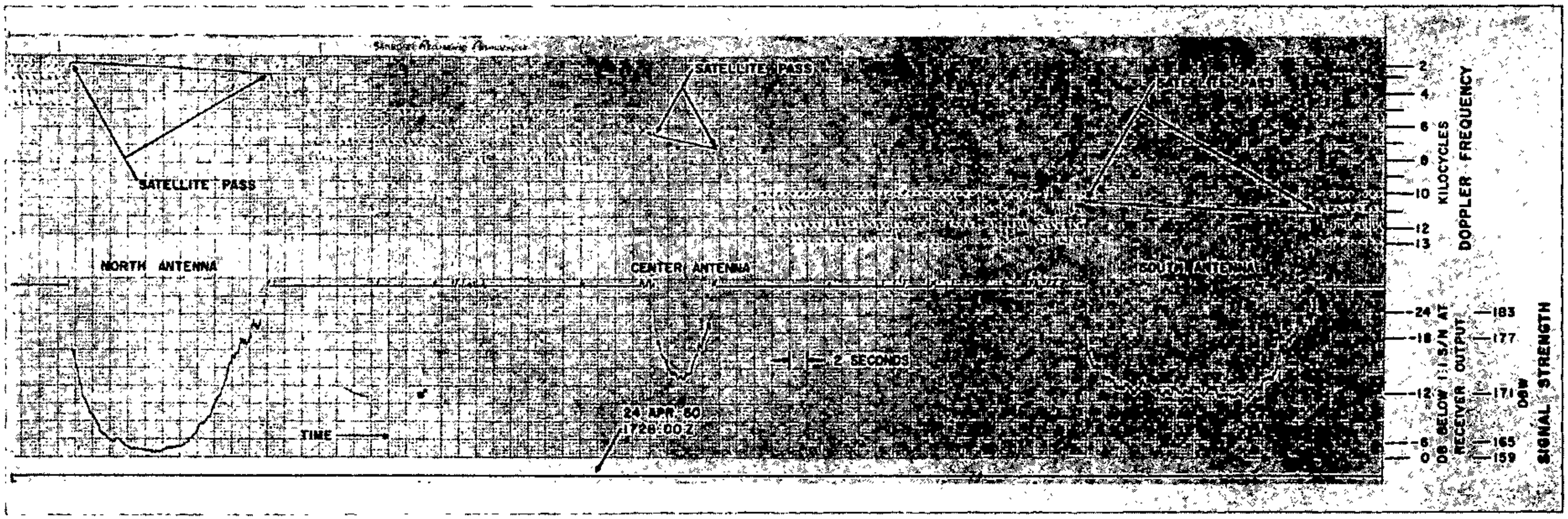


FIGURE 28 BLOCK DIAGRAM OF EQUIPMENT FOR FREQUENCY MEASUREMENT TESTS



ARPA - BRL DOPLOC DOPPLER RECORD OF
60 DELTA REV. 140, FORREST CITY, ARKANSAS
MEASURED 1728:06 Z, PREDICTED 1732 Z
ALTITUDE 116 MILES, 320 MILES EAST FT. SILL
NORTH - CENTER - SOUTH ANTENNAS, NORTH - SOUTH PASS

Figure 29

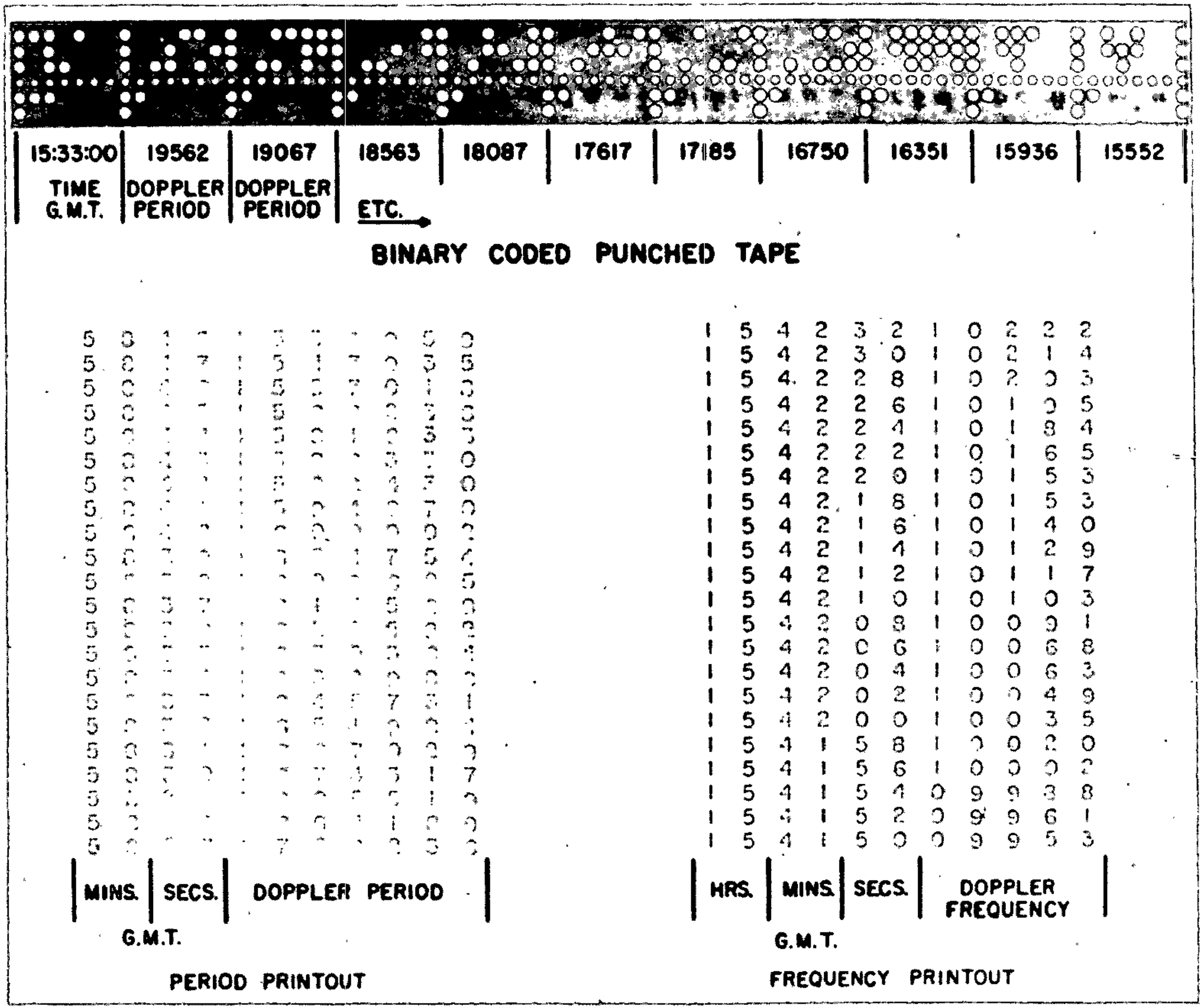


Figure 30 TYPICAL DOPLOC DATA OUTPUT

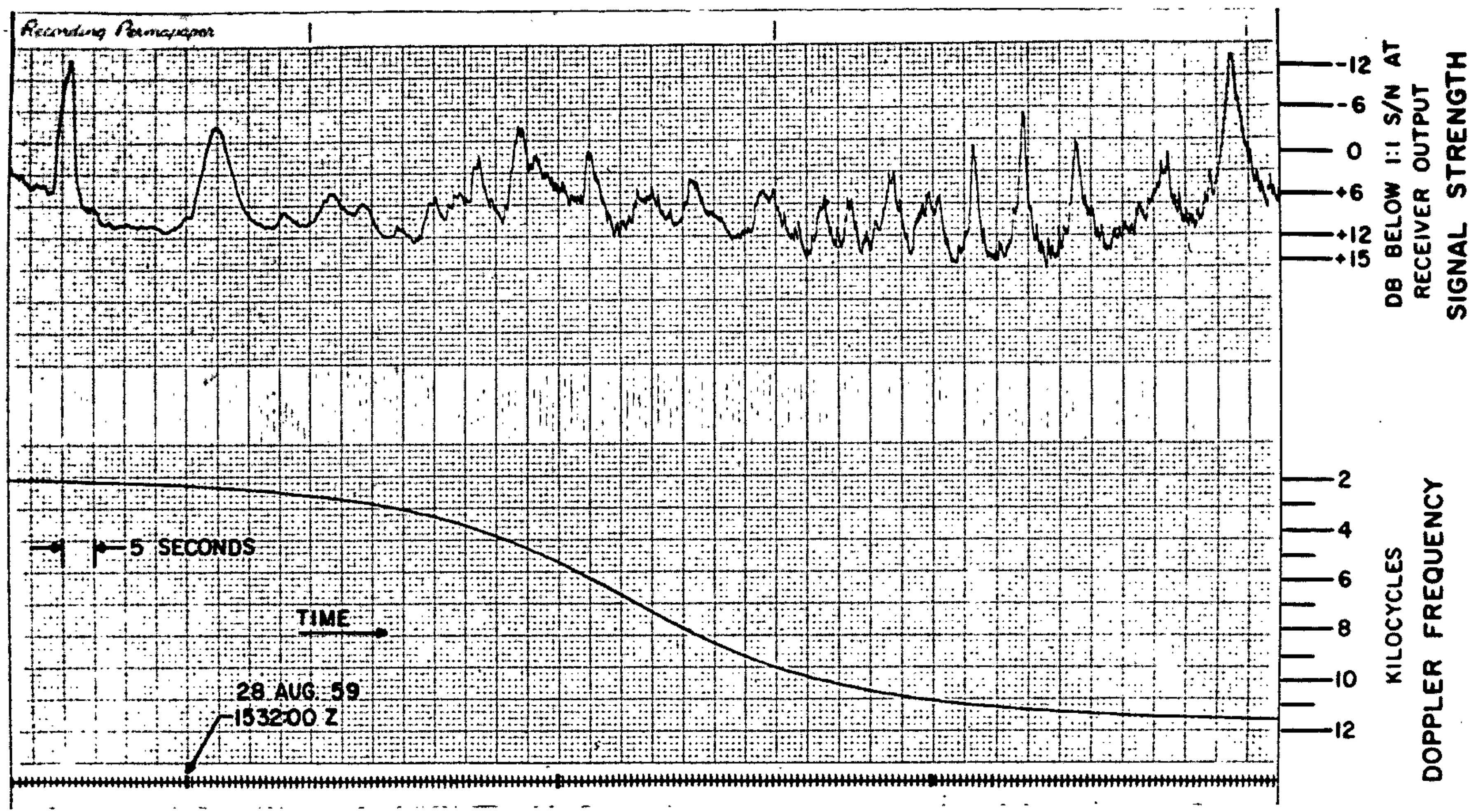


Figure 31a DOPPLER RECORD OF ACTIVE N-S TRACK OF 1959 ZETA (DISCOVERER VI) REV. 134 AT ABERDEEN PROVING GROUND, MARYLAND

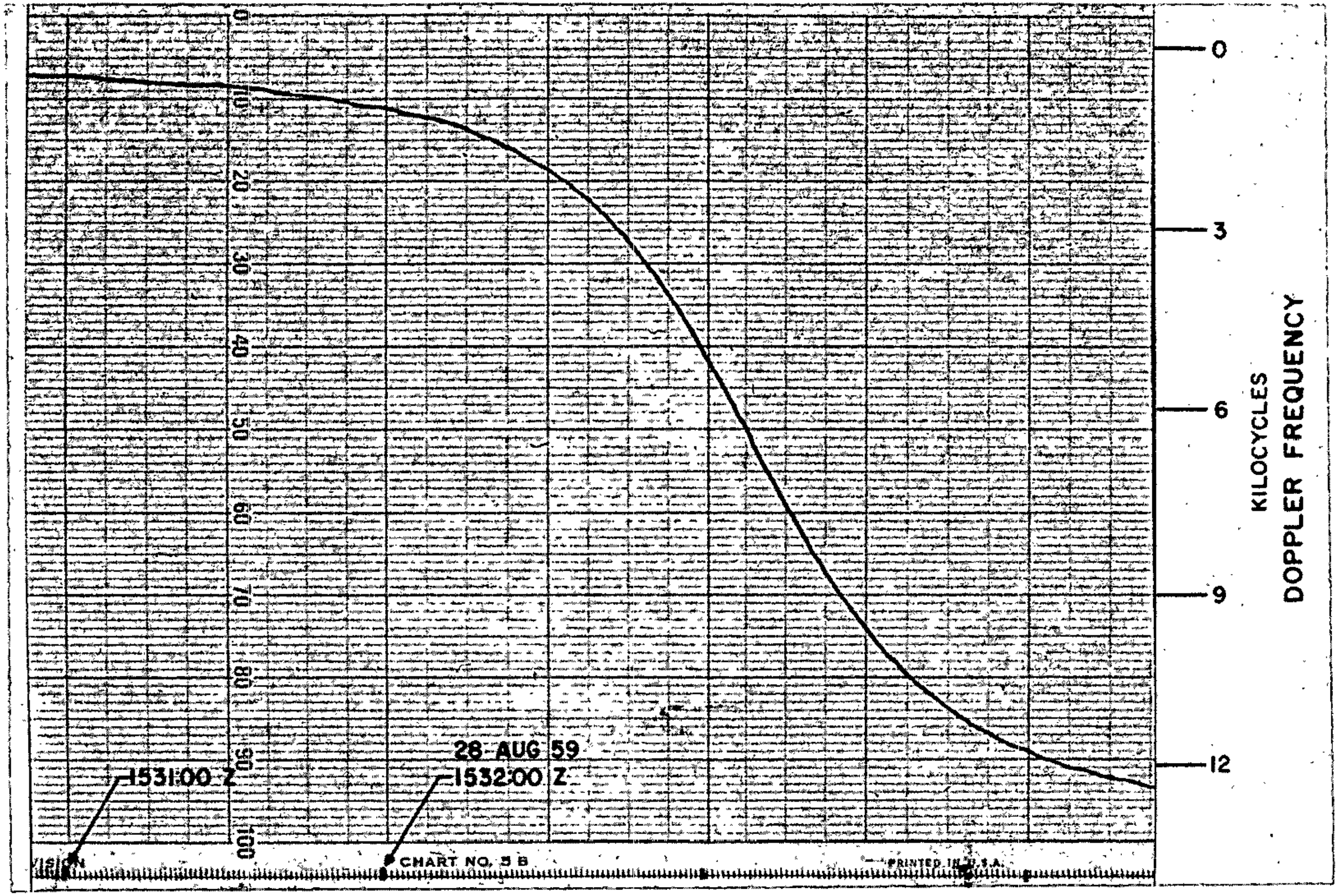


Figure 31b DOPPLER FREQUENCY RECORD OF ACTIVE N-S TRACK OF 1959 ZETA (DISCOVERER VI) REV. 134 AT ABERDEEN PROVING GROUND, MARYLAND

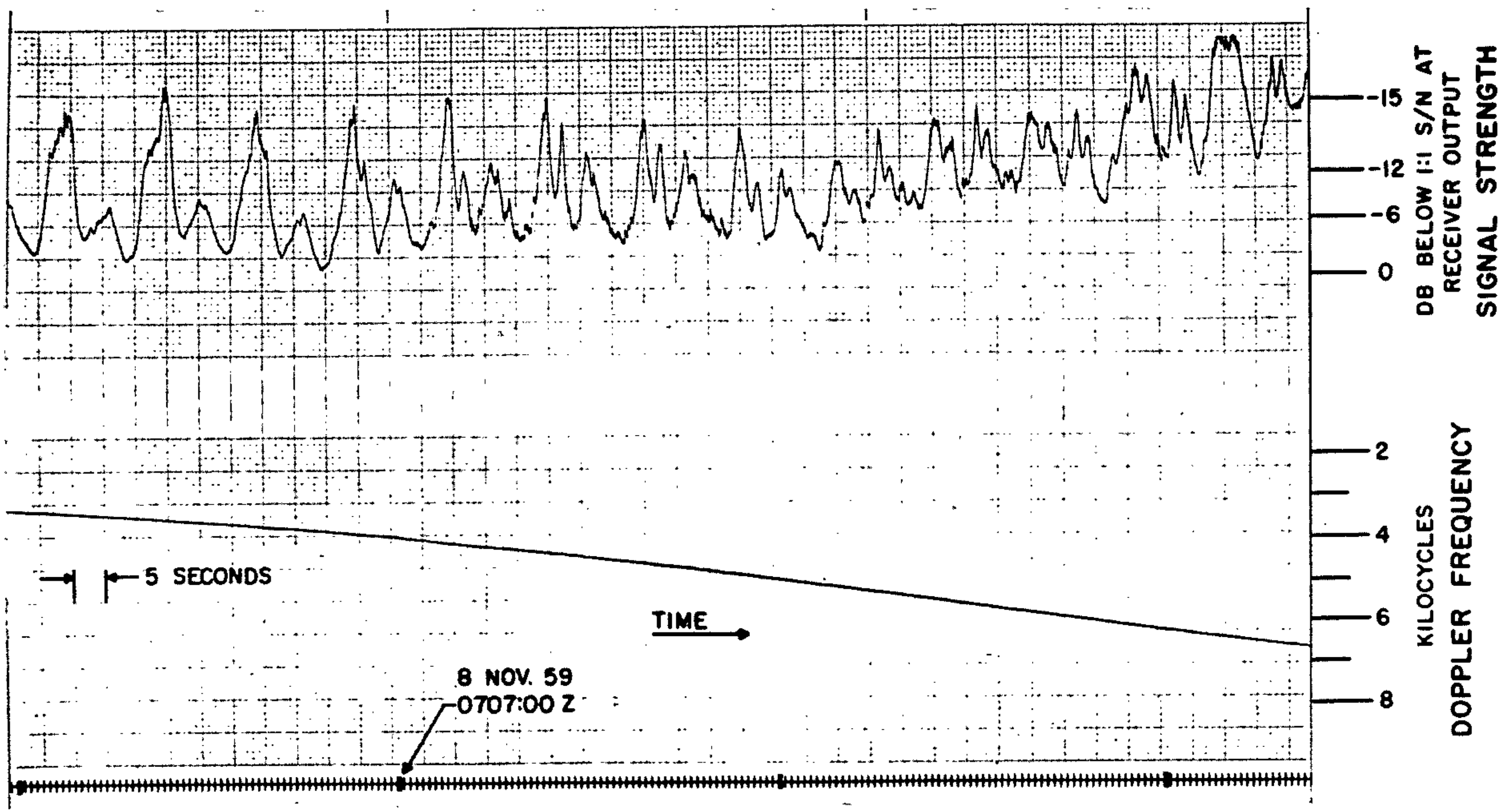


Figure 32a DOPPLER RECORD OF ACTIVE S—N TRACK OF 1959 KAPPA (DISCOVERER VII) REV. 7 AT ABERDEEN PROVING GROUND, MARYLAND

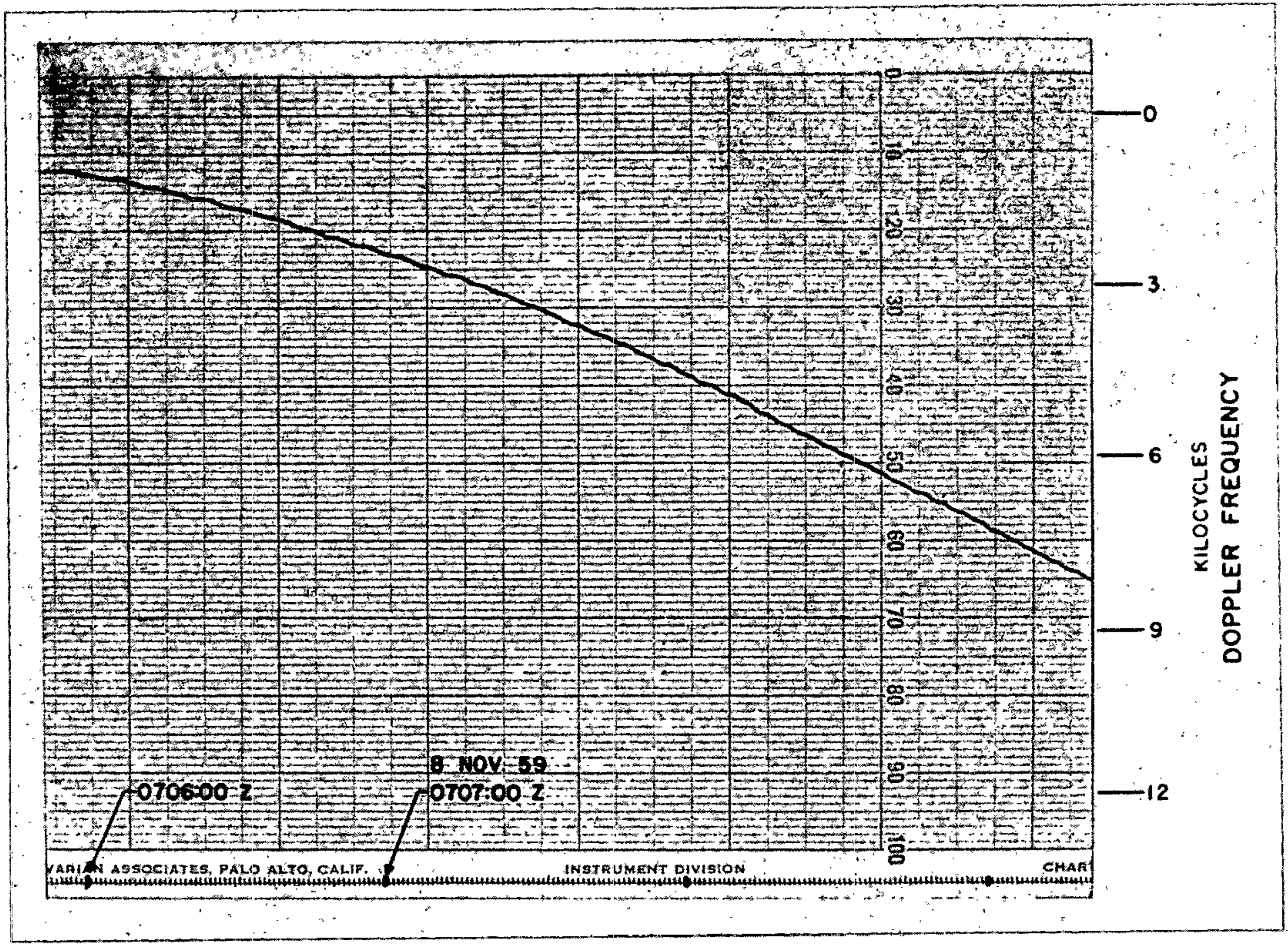
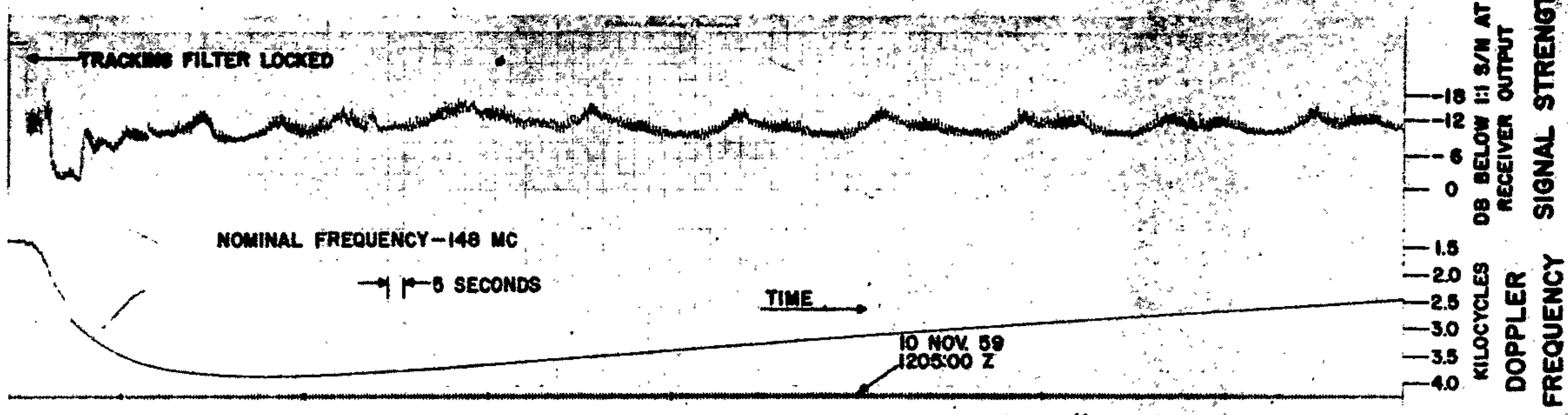
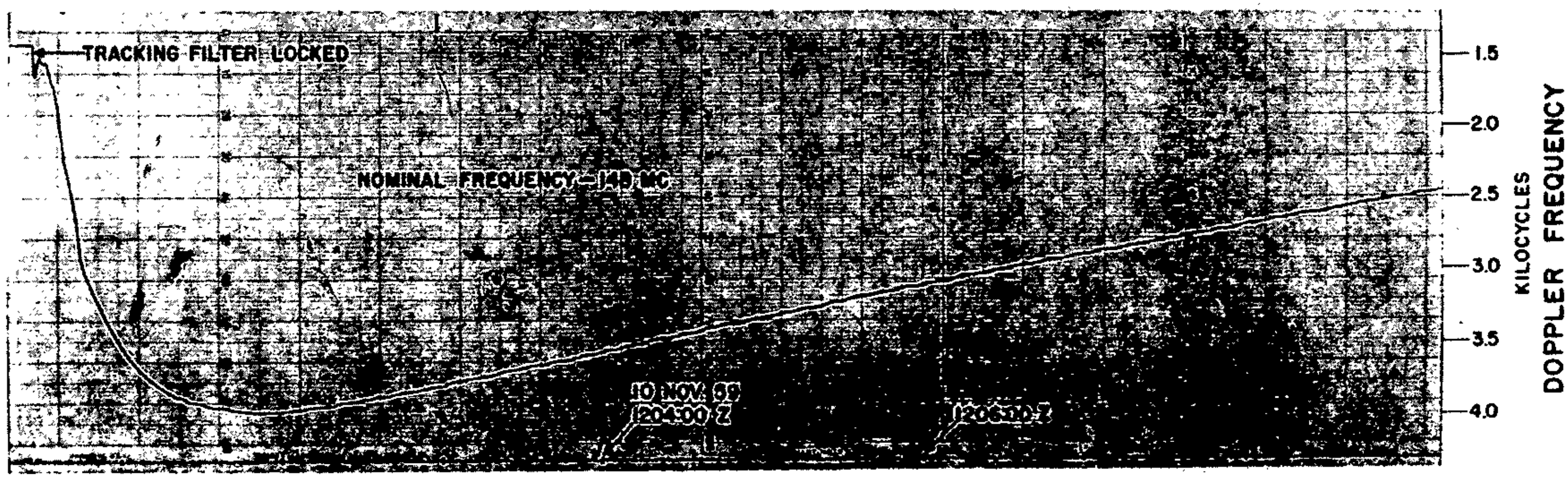


Figure 32b DOPPLER FREQUENCY RECORD OF ACTIVE S—N TRACK OF 1959 KAPPA (DISCOVERER VII) REV. 7 AT ABERDEEN PROVING GROUND, MARYLAND

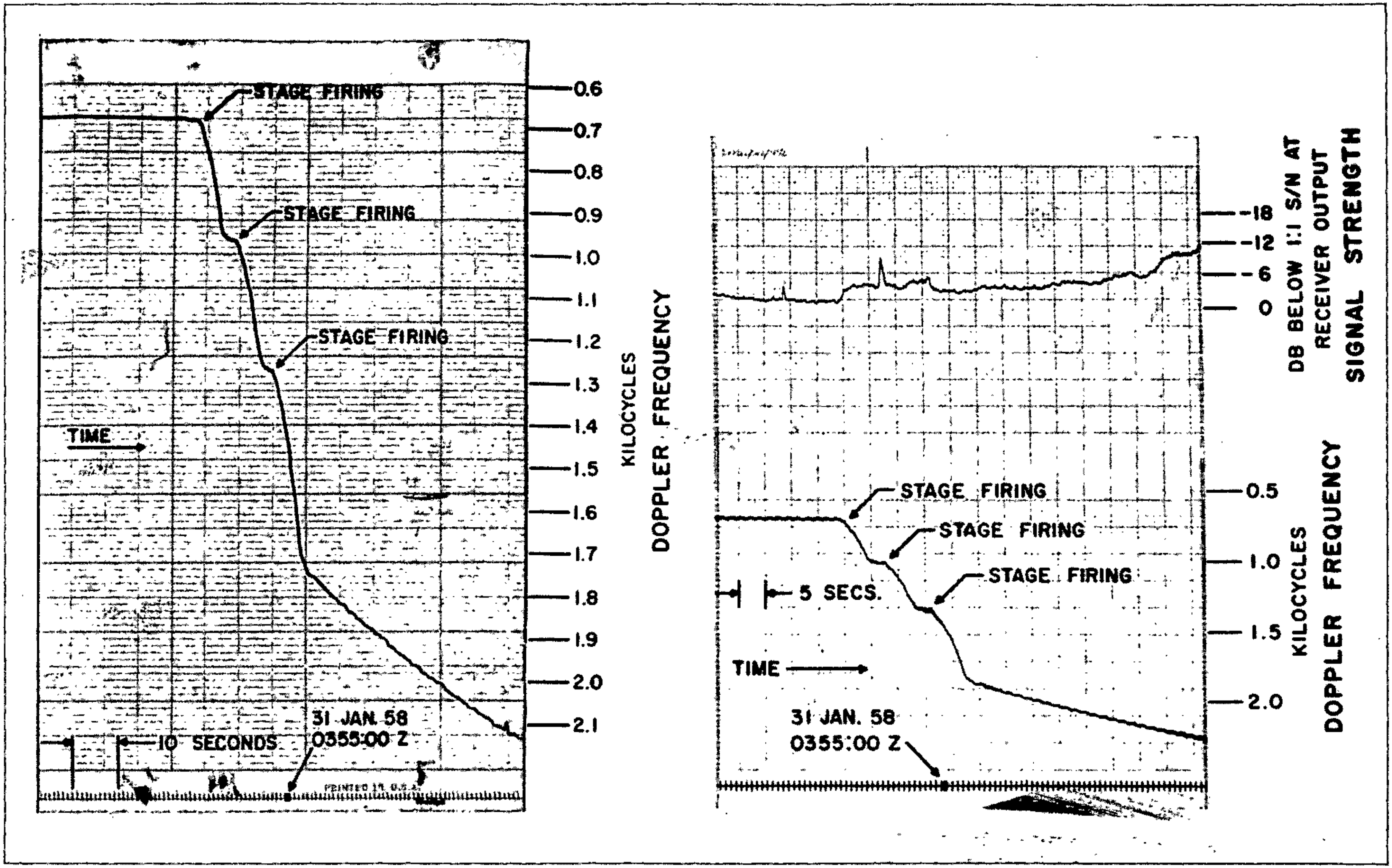


DOPPLER RECORD OF BRL IONOSPHERE PROBE (STRONGARM #1) LAUNCHED AT WALLOPS ISLAND, VA. AND TRACKED AT ABERDEEN PROVING GROUND, MD.



DOPPLER FREQUENCY RECORD OF BRL IONOSPHERE PROBE (STRONGARM #1) LAUNCHED AT WALLOPS ISLAND, VA. AND TRACKED AT ABERDEEN PROVING GROUND, MD.

Figure 33



DOPPLER FREQUENCY AND SIGNAL STRENGTH RECORDS OF THE LAUNCH OF EXPLORER I (58 ALPHA) TRACKED AT ABERDEEN PROVING GROUND, MD.

Figure 34

of the three receiving antennas. The step wave forms show the functioning of the automatic search and lock-on system used for acquisition of the reflected signal. The frequency range of the automatic search equipment was changed after satellite passage through one antenna beam, and search over a higher frequency range continued before satellite arrival at the next antenna beam. The lower channel indicates signal strength data received at the time of satellite passage at each antenna position. Calibration data for each channel are marked at the right of the record, and timing marks are indicated on the lower edge of the record.

Two types of recordings of Doppler data output are shown in Figure 30. The first is the Doppler period output recorded in binary code on standard five-level punched paper teletype tape. The first data block contains Greenwich Mean Time at the beginning of the recording run. Subsequent data blocks, recorded at the rate of one per second, contain the Doppler period measurement. The second type of recording is the printed record obtained from a Hewlett Packard, Model 560A digital printer. Two examples are shown. Each printed line contains Universal Time data and the Doppler data at print out time. When frequency is recorded the first six digits indicate time and the remaining five digits indicate Doppler frequency. When high resolution period measurements are desired, only four digits of time, minutes and seconds, are printed, allowing the remaining digits to indicate the period measurements.

Figures 31 and 32 a and b are typical examples of single and dual channel strip-chart records obtained at the DOPLOC stations during a tracking operation. The dual channel records contain signal strength data and Doppler frequency data, each indicated as a function of time. Time marks are on the lower edge of the chart. Calibration data for each channel are recorded at the beginning of each record just prior to the run. In these Figures the calibration data were transcribed from the original record and placed near the pertinent section of the record for clarity. The single channel records also contain the Doppler frequency as a function of time but allow higher frequency resolution because of the increased chart width.

The two similar sets of data are included to show the distinct differences in the records for two satellites. Figures 31 a and b show the data obtained during the tracking of 1959 Zeta (Discoverer VI) which passed almost directly over the receiving station, indicating a relatively steep frequency vs time curve (usually called the "S" curve). Figures 32 a and b show similar data recorded during tracking of 1959 Kappa (Discoverer VII) indicating a lower slope of the "S" curve because the satellite passage was at some distance from the receiving station.

Figure 33 shows the strip chart data recorded during the early portion of flight of the BRL ionosphere probe (Strongarm No. 1) on 10 November 1959. Data were obtained for approximately 24 minutes and included information over nearly the complete trajectory.

Figure 34 is an example of strip chart data recorded during a rocket launch. The Doppler data record obtained on 1958 Alpha (Explorer I) indicates step like shifts in frequency which correspond to rocket acceleration due to firing of successive stages. This type of data is very useful in determining the success of a rocket launching and the subsequent orbiting of a satellite.

Sample orbital parameters from the DOPLOC system are shown below. The first set is from passive tracking of revolution 124 of 1960 Delta and the second is from active tracking revolution 34 of 1960 Gamma 2. The data are compared with the published results of Space Track, Bedford, Massachusetts.

1. 1960 Delta (Discoverer XI) Rev. 124 (Passive)

	DOPLOC (Statute Miles)	SPACETRACK	DIFFERENCE
Semi maj. axis	4115	4121	-6
Eccentricity	.0198	.0177	.0021
Inclination	80.31°	80.10°	.21°
Right Ascension of Ascending Node	207.50°	207.27°	.23°
Argument of Perigee	97.49	125.22	-27.73°
Mean Anomaly at Epoch	40.17°		

2. 1960 Gamma 2 (Transit IB) Rev. 34 (Active)

	DOPLOC (Statute Miles)	SPACETRACK	DIFFERENCE
Semi maj. axis	4313	4309	4
Eccentricity	.0213	.0394	-.0181
Inclination	51.40°	51.22°	.18°
Right Ascension of Ascending Node	267.21°	266.75°	0.46°
Argument of Perigee	321.17°	277.15°	43.62°
Mean Anomaly at Epoch	141.07°		

BRL Report No. 1123 contains a summary of the tracking activities of the BRL DOPLOC stations for both active and passive type tracking.

IV. THE FULL SCALE DOPLOC SYSTEM CONCEPT

A. Introduction

Amendment No. 3 to ARPA order 8-58 provided funds for a supporting research program with a goal of arriving at recommendations and specifications by July 1960, for an "ultimate" full scale Doppler type satellite detection and tracking system. The tentative conclusions of systems engineering studies were outlined to ARPA representatives at a meeting at BRL on 14 April 1959 and briefly described in BRL Technical Note No. 1266, "An Approach to the Doppler Dark Satellite Detection Problem", by L. G. deBey.

This desciption did not attempt to justify the concept presented nor to derive quantitative parameter specifications. In the interest of publishing the general concept at an early date, the result of a number of studies which had been under way for some time were largely omitted. This section of the technical summary report presents the proposed "ultimate" DOPLOC fence in somewhat greater detail and includes changes in design parameters which resulted from continuing studies.

B. The Interim DOPLOC Complex

The interim fence, which was designed and installed before the R & D program was initiated, made use of essentially off-the-shelf items of technical equipment and was intended to provide a capability of detecting one square meter targets at maximum altitudes of 500 to 1000 miles. This system employed antennas having east-west fan beams of 8 x 76 degrees (16 db gain) directed to produce one vertical beam and two beams at elevation angles of 20^{o}, one toward the north and the other toward the south. It can be shown that to meet the full ARPA design objectives the transmitted power required with these antennas would be about 30 megawatts, assuming parametric receiver front ends (1 db NF), cosmic noise level 3 db above receiver noise, 10-cps bandwidth, 10-db output signal-to-noise and an operating frequency of 108 mc. Such power levels in a single illuminator installation would be difficult to obtain. Also several such installations would be required to cover the space volume above the United States. This situation led to an attempt to find a means of improving the gain of the antennas and of using them more efficiently.

C. Design Objectives

Firm requirements of system performance or specifications were not issued by ARPA during this design period. Instead, a number of design objectives were informally stated in various technical conferences dealing with the dark satellite fence problem. These objectives, when viewed from the standpoint of a system employing Doppler techniques, gave rise to certain specific system requirements which more nearly represent specifications. The following tabulations contain lists of these objectives and specific Doppler system requirements around which the full scale Doppler satellite passive detection and tracking system was planned.

1. Detection Range. All objects in orbit between altitudes of 100 and 2000 statute miles. It is now believed that all objects having effective reflection areas greater than 1 square meter can be tracked over the range of 100 to 3000 s. miles.

2. Target Size. All objects below 2000 s. miles whose effective radar cross section is 0.1 square meter or larger.

3. Multiple Object Capability. System should be capable of handling multiple objects. Maximum number not specified. Design objective is capacity for the order of 100 - 1000 objects in orbit over the United States at one time.

4. Detection Probability. The system should not permit "sneak" satellites to pass; the fence should be tight.

5. Period Calculations. Accurate to within 1 - 5 seconds.

6. Orbit Inclinations. All.

7. Time of Arrival. 1 - 5 seconds.

8. Accuracy, Aximuth and Elevation. 0.1° to 0.5°. Resolution 500 - 5000 feet.

9. Time Required for First Orbit Determination. Less than 20 minutes.

10. Identification. Indication of size and direction of motion. Would monitor emissions and indicate tumbling or stability of flight.

11. Adequate Data for Correlation with Known Orbits.

12. No counter-countermeasure provisions except for extreme narrow banding of receiving equipment.

Based on the use of Doppler techniques and the mathematical solution required to derive orbital parameters from such data, the following specific system requirements are postulated:

1. A minimum of twelve Doppler frequency measurements must be obtained for low altitude satellites and twenty-five or more frequency measurements for medium to high altitude satellites.

2. The system must track the satellite over a segment of its orbit corresponding to at least 150 seconds of flight time for low altitude satellites and for 600 seconds of flight time for maximum altitude satellites. This tracking need not be continuous, but may consist of a number of short segments.

D. Target Size

The objectives outlined above were not based on a formal investigation of the potential threat created by the technical feasibility of orbiting dark satellites. Rather they constitute good guesses as to the proper order of magnitude. Doubt exists that the value of the minimum detectable target size is realistic. It is difficult to imagine that a satellite about 20 inches in diameter, which would have an effective reflection cross section area of 0.1 square meters at 100 mc if uncamouflaged, would pose a serious threat, from the reconnaissance point of view, at an altitude of 2000 miles. It is conceivable, however, that satellites of larger physical size could be camouflaged to make them appear as 0.1 square meter targets, the degree to which this can be accomplished being dependent upon size, camouflage weight, frequency-bandwidth considerations, effect on flight performance and economic factors. Since arbitrary specifications of a target two or three times smaller in effective cross section than that which can be expected to perform a useful reconnaissance function would require

antenna gains or transmitter power larger by these same factors (involving cost increases of millions of dollars) an economically sound proposal for an "ultimate" system could not be assumed. Thus an investigation to aid in establishing a realistic target size was deemed to be required. Such a study was initiated within the Ballistic Research Laboratories but did not progress sufficiently to justify a report at the closing of the project.

E. Antennas

A number of beam configurations and combinations were studied and discarded because they did not appear to meet all of the system requirements. Fixed fan beams spaced every few degrees would provide enough data points but would require large numbers of antenna arrays and independent high powered driving transmitters with attendant high cost. High gain pencil beams, scanning to give adequate volume coverage, would reduce the power of individual transmitters, but would require large numbers of costly arrays and transmitters in order to provide a tight fence (each pencil beam transmitter receiver would have to track a given satellite to obtain enough data, thus leaving the fence "open" for other satellites). Furthermore, with a bi-static system in which transmitter and receiver pencil beams emanate from different surface locations, the beams intersect only at a small volume or cell in space at any instant. To provide the required complete coverage, one beam would be required to scan the length of the other while it was scanning, and thus would use too much time, permitting other areas to go unmapped, or satellites to cross other areas undetected.

As a result of the above considerations it was decided that a fan shaped beam was required. The dimensions of the beam were then to be determined. Because of the curvature of the earth it is not possible to have more than one transmitter and one receiver scan a given area in a coplanar manner such that the receiver will always see all objects illuminated by the transmitter. To scan even one pair of antennas together requires that the scan axis be the chord of the earth circle between the two antenna stations. The wide dimension of the fan is determined primarily by the distance between the two stations, which in turn is dictated

by the minimum radiated power required to detect a minimum size target at 2000 to 3000 miles altitude. The dimensions of the United States, indicated that a base line of approximately 1000 miles was about correct. At greater distances, low altitude satellites would not be seen at all points between the stations, while for smaller separations of stations, full advantage would not be taken of available power. Early estimates indicated that the beam dimensions should be about 60° by 1°. Further study resulted in the adoption of a 60 x 1.4 degree fan beam, scanned from horizon to horizon.

F. Signal Dynamics

The maximum Doppler frequency, using 108 mc for a satellite in orbit at 100 miles altitude approaching a DOPLOC complex in a plane of a great circle through the stations is 6000 cps. The maximum first derivative f_d of the frequency-time curve is about 100 cps^2. For a circular orbit at an altitude of 2000 miles f_d will be approximately 9 cps^2. The minimum information bandwidth required to accommodate Doppler signals with these rates of change of frequency is given by:

$$B_i = \sqrt{f_d}$$

For h = 100 miles, B_i = 10 cps; while for h = 2000 miles, B_i = 3 cps. Since the received signal is expected to be less at the higher altitude, it is fortunate that a smaller information bandwidth is tolerable since it is extremely important to utilize the smallest practical bandwidth. BRL experience has shown 2.5 cps to be about the minimum useful bandwidth for 108 mc. This lower limit is due to phase pertubations introduced by the antennas and the propagating medium.

The maximum signal processing or integrating time is given by:

$$T_i = \frac{1}{B_i}$$

T_i ranges from 0.1 second when a 10 cps filter is used to 0.33 seconds when a 3 cps filter is used. Gabor[3] and Woodward[4] derive an expression

for the uncertainty of frequency measurement.

$$\Delta f = \frac{1}{T_1 \sqrt{s}}$$

where s is the power signal-to-noise ratio. For a phase locked tracking filter of the type used in the DOPLOC fence the minimum usable signal-to-noise ratio has been experimentally shown to be about 4 db. Since other types of narrow band frequency measuring equipments might require a greater signal-to-noise ratio, a safety margin was provided by assuming a required output S/N = 7 db. The frequency uncertainty (Δf) is thus dependent upon integration time assumed and will be either 1.4 cps or 4.5 cps for integration times of 0.33 and 0.1 seconds, respectively. The result of orbit computations containing random errors of frequency measurement of these same general magnitudes show that the accuracy of the solution is not seriously degraded by such errors.

Shorter integration times result in higher noise-to-signal ratios, deteriorate the accuracy of frequency measurement and reduce detection range. A heavy penalty is paid in terms of total transmitter power required by even a twofold increase in bandwidth. The minimum signal duration (integration time) cannot be appreciably less than 0.1 seconds. Conversely an increase in the integration time above the value of 0.33 seconds would reduce the bandwidth below 3 cps.

For the scanning antenna system proposed, the maximum signal processing time is equivalent to the time required for the narrow dimension of the scanning fan beam to pass over the target, the time on target (t_T) and is equal to:

$$t_T \text{ (max)} = \frac{\text{Beamwidth } (\theta)}{\text{Scan Angle Velocity } (w)}$$

Conversely for a given t_T, the beamwidth is:

$$\theta = wt_T$$

The angular scan velocity is determined by the number of data points required

and the total time the target is within tracking range. These factors vary as functions of target altitude. At low altitude the slope of the Doppler curve is high and fewer data points are required. Fewer than six points on the Doppler curve will not yield a solution, even in theory. Experience has shown 12 - 15 points to be adequate. With close approach satellites at high altitudes, the slope is low and the "S" curve has much less character, requiring more data points to obtain a solution.

The time the target is within tracking range, T, is summarized in Table I, and ranges from 192 to 1000 seconds. The angular scan rate, W, is given by

$$W = \frac{N_D \phi}{T}$$

where N_D = number of data points required. ϕ = scan angular coverage.

The lowest value of total time for tracking, T, must be used since this will determine the maximum scan rate. Thus for:

$$\phi = 160^\circ$$

$$N_D = 12$$

$$T = 192$$

$$W = \frac{12 \times 160}{192} = 10^\circ/\text{second}$$

One scan period is thus $T_s = \frac{\phi}{W} = \frac{160}{10} = 16$ seconds.
The number of data points which can be obtained for targets at higher altitudes may be obtained through the use of the expression $N_D = \frac{t}{T_s}$.
Representative values of N_D for selected altitudes are given in table IV - 1.

TABLE IV - 1

MINIMUM NUMBER OF DATA POINTS VERSUS ALTITUDE*

Altitude Miles	V M/Sec.	S Miles	T Sec.	Number Data Points
100	4.98	960	192	12
200	4.79	1560	326	20
400	4.68	2460	525	33
1000	4.40	4400	1000	62
1500	4.18	3900	932	58
2000	4.00	2440	610	38

*For circular polar orbit

V = Satellite velocity at altitude specified.

S = Length of observed satellite path in antenna coverage volume.

T = Total time during which satellite may be detected.

G. Antenna Gain

The minimum effective narrow dimension of the composite fan beam system, comprised of two coplanar fan beams, can now be determined by the relation:

$$\Theta = W t_T$$

The minimum value of Θ will be obtained when t_T is smallest. The time on target, t_T, was shown previously to have values between 0.1 and 0.33 seconds depending on the beamwidth required by signal dynamics. Thus the minimum effective beamwidth is:

$$\Theta = 10 \times 0.1 = 1 \text{ degree}$$

Although larger values of t_T would allow the use of greater beamwidths the resultant lower gain of the antenna system would force the use of higher transmitter powers or would reduce the output S/N ratio. On the other hand, the fact that the reciprocal of the narrowest bandwidth (3 cps) allows an integration time as great as 0.33 seconds does not

mean that this full time must be used unless the lowest value of frequency uncertainty must be achieved. It has been shown that the uncertainty equivalent to integration times of 0.1 seconds is adequate for the dark satellite problem. It is thus advantageous in establishing the remaining system parameters to assume $\Theta = 1$ degree (effective). The effective value of Θ is stressed intentionally. Each of the two coplanar beams introduces a 3 db pattern factor at the design beamwidth and the total loss due to pattern factor is 6 db. In order to achieve an effective beamwidth of one degree at the 3 db point the individual beams must each introduce a pattern loss of only 1.5 db at a beamwidth of 1.0 degree. Antennas having 1.4 degree beamwidth at the three db points will yield an effective system beamwidth of 1.0 degree. The fan beams required would thus have cross sections of about 1.4 x 60 degrees at the 3-db points. The gain of an antenna in terms of its beam dimensions is given conservatively by:

$$G = \frac{0.7 \times 41200}{\phi \times \Theta} = \frac{28840}{1.4 \times 60} = 344$$

$$G_{db} = 10\log 344 = 25 \text{ db.}$$

It should be noted that economic signal dynamic, and data quantity considerations determine the minimum tolerable beam dimensions and hence the maximum antenna gain which may be used. The proposed DOPLOC satellite fence was thus an antenna gain limited system. This factor had an important bearing on the choice of optimum operating frequency.

Having determined the antenna beamwidths and gain, the next problem was to find a design which would be economically and physically practical in size and cost, and which would provide for the necessary angular scan without serious degradation of the beam shape. This problem resulted in an extensive engineering study both by BRL and by prospective contractors who were requested to submit bids on a scaled down model of the scanning antennas and transmitter for the "ultimate" DOPLOC system. On first consideration it appeared that a Wullenweber type antenna design mounted with its normal diameter in a vertical plane would provide for the necessary scan operation. The first idea was to feed the various transmitting elements

of the Wullenweber antenna from commutated low power circuits in such a manner that the required number of antenna elements was fed sequentially around the rim of the antenna. Further study showed however that when the beams from the Wullenweber antenna are tilted off the axis of the antenna system and then scanned, the beam breaks down into a conical shape and will not perform the required scan at low angles. This subject will be treated in more detail in connection with the proposal submitted to ARPA. Suffice it to say here that satisfactory antenna designs were derived.

H. Received Signal Power Required

The minimum usable received signal power which will provide suitable DOPLOC data is determined by the following factors: 1) External noise, 2) Internal noise, 3) Bandwidth, 4) Output signal-to-noise ratio. These factors are discussed in relation to the "ultimate" DOPLOC system.

1. External Noise. Noise sources external to the DOPLOC system are expected to provide the major noise contributions for a carrier frequency in the range of 100 to 150 mc. These sources are extraterrestrial such as cosmic and galactic as well as of local origin such as automobile ignition, diathermy or other man made interference. Cosmic noises from the galactic plane and extragalactic regions are the most continuous sources of extra-terrestrial noise, with occasional periods of solar noise when the sun is excited. High intensity, discrete radio star cosmic noise sources, most of which have angular dimensions less than 1° will produce a strong pulse of noise when the high gain receiving fan beam sweeps past them. These noises did not prove to be serious since they could at worst only interfere with a few data points.

The amount of extraterrestrial noise available at the input to the receiver is a function of the antenna pattern width and the region of the sky in the beam at the moment. As the beam sweeps across the galactic sector which is about 15 to 30 degrees wide it crosses the region of highest cosmic noise density. Therefore it was necessary to design the system to operate in the presence of this noise. The relation between the amount of noise picked up and the antenna gain and beamwidth is a complex function of

the orientation of the antenna and its gain level. When an antenna is oriented toward the galactic plane, its noise output will initially increase as its beam width is decreased. However, a limit is reached where a further decrease in antenna beamwidth (corresponding to an increase in gain with a point source) will not appreciably increase the cosmic noise received. This limit is between 10 and 15-db antenna gain. When an antenna is directed off the galactic plane and the noise is uniformly distributed in space, the cosmic noise received is independent of antenna beamwidth or gain. The proposed 1.4 x 60 degree antenna with 25-db gain is considerably over the 15 db gain limit for increasing cosmic noise. The noise measurements made with the interim DOPLOC antennas, which had 16-17 db gain, should apply directly. The cosmic noise measurements made with the interim DOPLOC center antennas showed a maximum noise temperature of less than 1160° K, 99 per cent of the time. This temperature corresponds to a noise power of 1.6×10^{-20} watts per cps bandwidth.

Atmospheric and local noise sources that have been observed include lightning, ignition, power lines and electrical equipment. The noise from these sources is generally of the impulse type, consisting of very high intensity, short duration pulses that contain very little energy and are not expected to seriously affect tracking for an appreciable portion of time. Sand static can also be a problem in desert areas where the antennas are exposed to blowing sand.

2. Internal Noise. A preamplifier with a 2-db noise figure is attainable in the 100 to 150 mc region with vacuum tubes. The internal noise for a 2-db noise figure is 2.4×10^{-21} watts per cps bandwidth. This does not include the source resistance noise which for the DOPLOC system is the antenna with its associated noise temperature. The total of the antenna noise plus the receiver noise is, $1.6 \times 10^{-20} + 0.24 \times 10^{-20} = 1.84 \times 10^{-20}$ watts per cps bandwidth.

3. Bandwidth. The bandwidth required in the receiving equipment is dependent on both the orbital parameters of the satellite and on the design of the receiver. The method and amount of bandwidth limitation prior to

final detection is also dependent on the characteristics of the detection system used in the receiver. The RF section of a DOPLOC receiver may be relatively conventional. The response should be linear with input signal for the range of signals and noise which must be received. The receiver should be free of regeneration and oscillation tendencies, and its phase characteristics should be relatively unaffected by variation of amplification. The output bandwidth of the IF amplifier should pass the maximum Doppler frequency, and should preferably be adjustable to quite narrow values when it is possible to eliminate the noise by narrow banding techniques. The interim DOPLOC receivers used about 15-kc bandwidth in the i.f. amplifier section, but through the use of phase-locked tracking filters in the output circuits obtained the effect of pre-detection bandwidth reduction. The tracking filter operated at bandwidths of 2.5 to 10 cps.

I. System Geometry and Coverage

The purpose of the original DOPLOC proposal was to provide satellite detection coverage to the volume of space above the United States. No counter measures were to be initiated. The principal goal was to detect and identify every object passing over the protected area with a known orbit, or to compute a new orbit if the pass were the first one for a given satellite. The spacing between the transmitter antenna and the receiver antenna was determined primarily by the altitude limits over which the system was to operate. As indicated above the two antennas were to either physically rotate or to cause their beams to sweep around an axis formed by an earth chord by drawing a straight line between the two stations in the plane of the great circle containing the two stations. The range along the earth's surface to the sub-target point, for a target at 100 miles altitude is 420 miles when the angle between the horizon and the line of sight to the target is 10 degrees. Based on these data it would seem to be necessary to place the stations every 420 miles or less apart. Greater spacing would permit volumes of space in which 100 mile targets would not be seen even though they were between the stations. However, because of the beam broadening and side lobe effects, and also because of the proximity of 100-mile objects to the system, the distance between the stations can be extended to 1000 miles without leaving serious dark areas for low flying objects.

It is of course not sufficient merely to detect the object. It must be tracked over a large enough segment of its path to permit the orbit parameters to be determined. The time the target is within tracking range is a function of its altitude and the volume coverage of the tracking system. The volume coverage, conversely, can be determined by the minimum permissible time the target must be tracked at a given altitude. For example at an altitude of 2000 miles this minimum time for satellites in circular orbits is 610 seconds while at 100 miles this time is about 150 seconds. At the higher altitude the satellite velocity is about 4 miles per second and the distance travelled along the orbit during the 610 seconds is 2440 miles. The bi-static DOPLOC system must then have a capability of tracking the target along this segment of its path.

Figure 35 shows the transverse coverage of the nodding or scanning antenna. The coverage radius (2237 miles) intersects the 2000-mile altitude surface at points 2440 miles apart thus providing the capability of tracking the target along the required segment of the orbit. Table IV - 1, page 111, shows the length of orbit segment for various values of altitudes between 100 and 2000 miles and the times required for satellites in circular orbits to traverse these distances.

The proposed patterns and coverage of two antennas of the nodding type in a plane containing the base line, are shown in Figure 36. The area of coverage is approximately bounded by the earth's radii extended through the two stations, these radii lying in the plane of coverage shown in the previous figure. One range, transmitter to target, has been determined above as being 2237 miles maximum. The other range, target to receiver, is approximately 2450 miles maximum.

The total volume of space swept out by one of these nodding antenna systems, and thus the volume coverage of one transmitter receiver pair, is shown in Figure 37. Total coverage would depend upon the number of transmitter receiver pairs employed and upon their deployment.

Figure 38 illustrates a possible location of stations within the United States. A pair of transmitters, T_1 and T_2 would be located at about 40 degrees north latitude and 98 degrees west longitude. Receivers R_1 and R_2

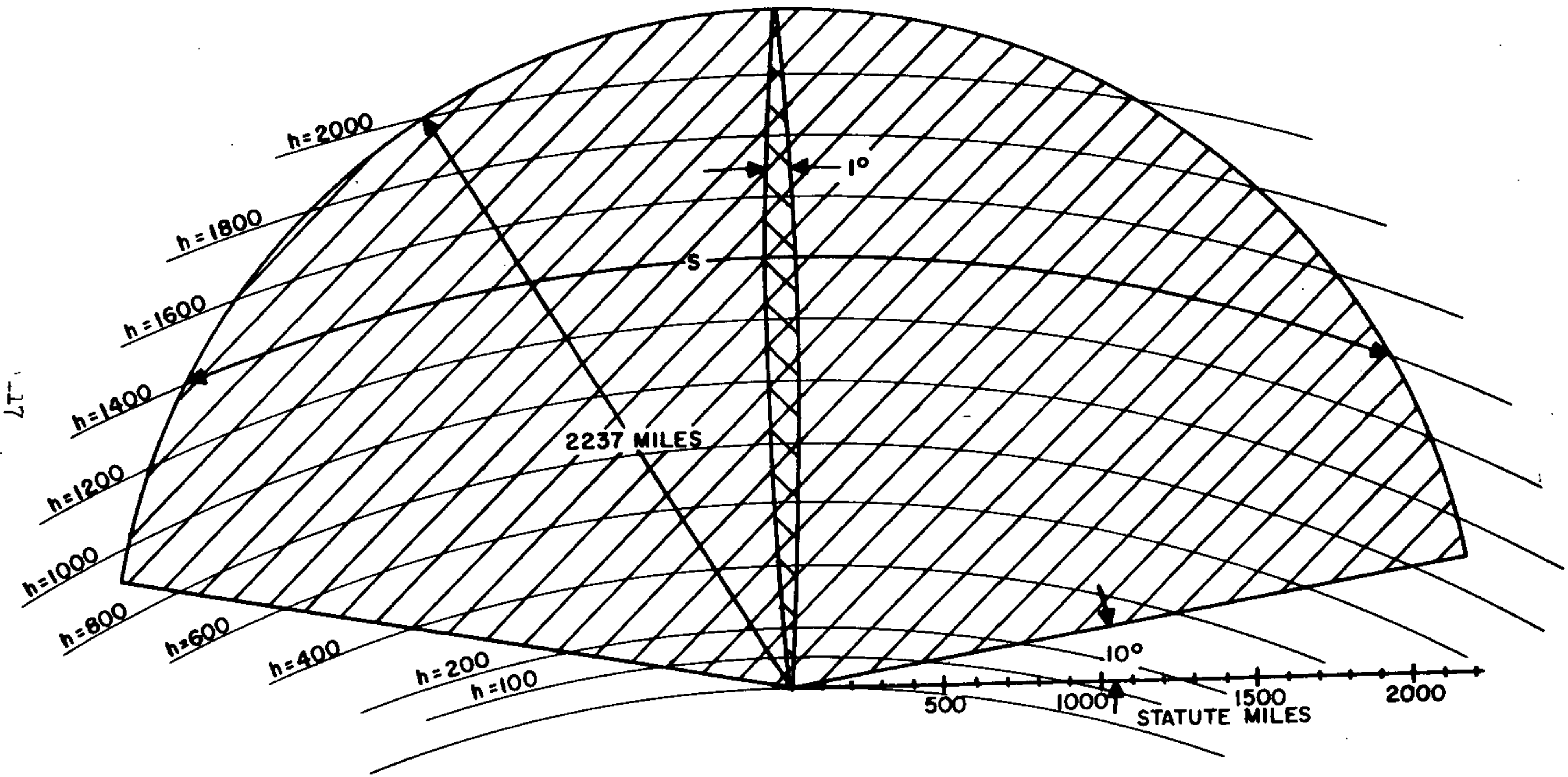
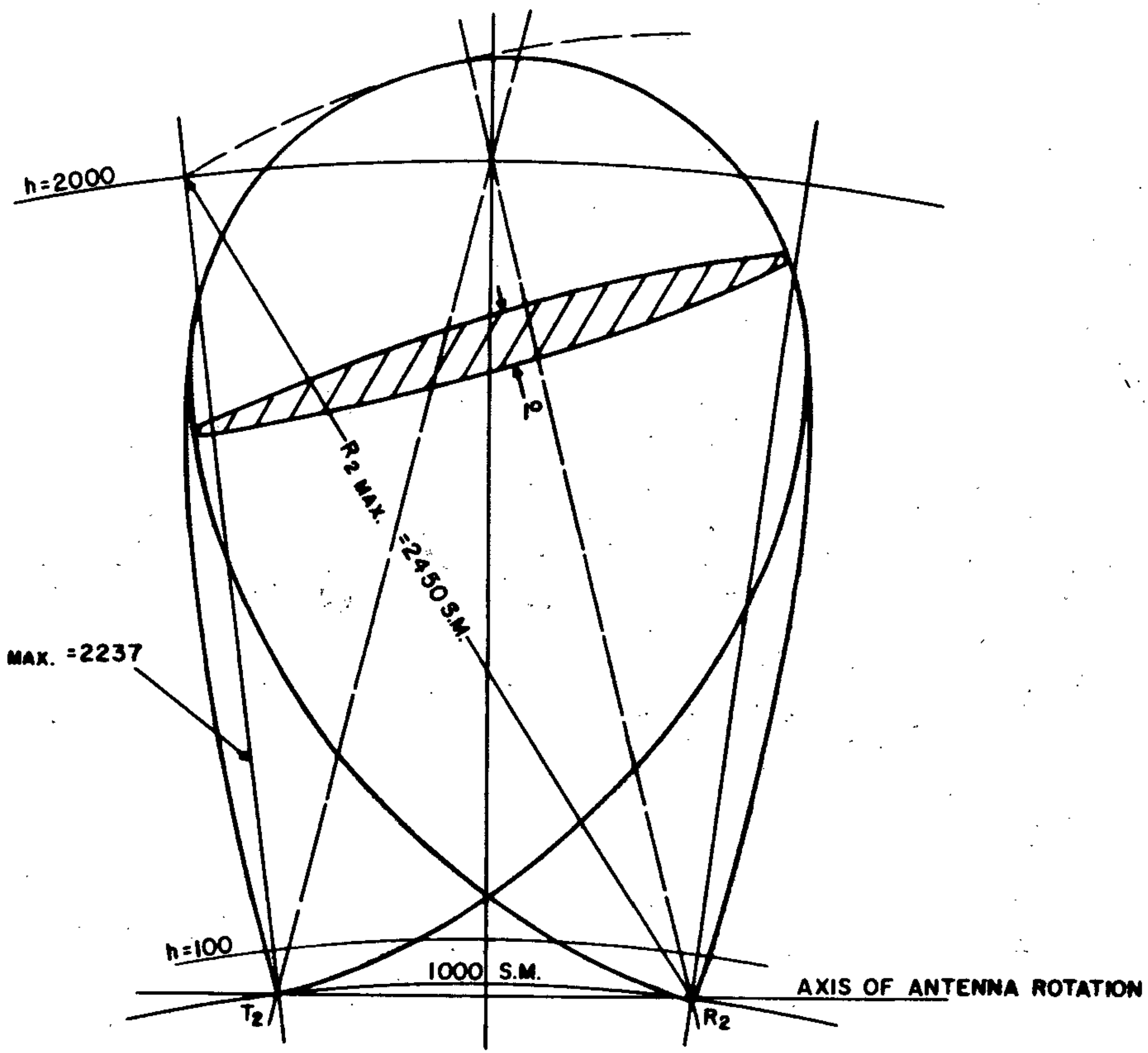
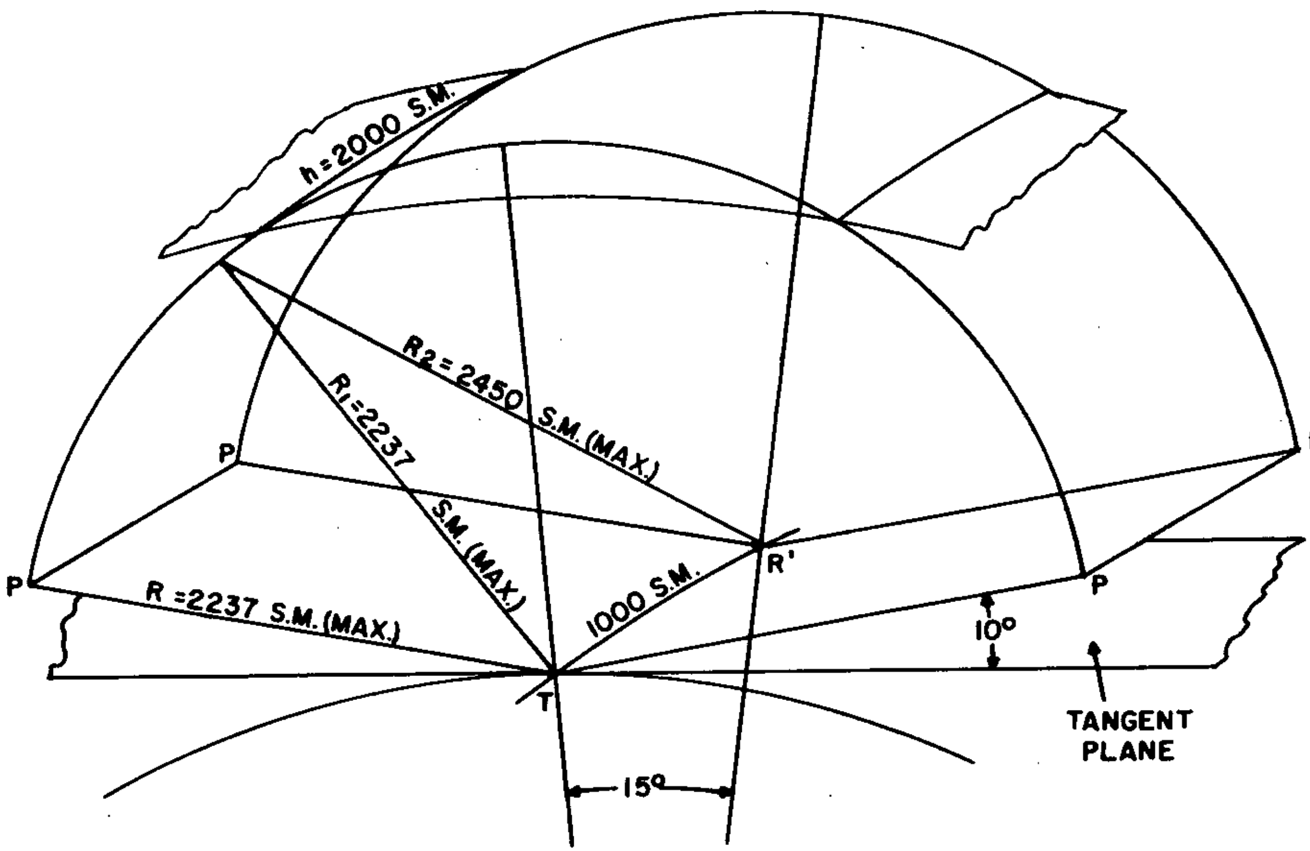


FIG. 35 SCANNING BEAM TRANSVERSE COVERAGE

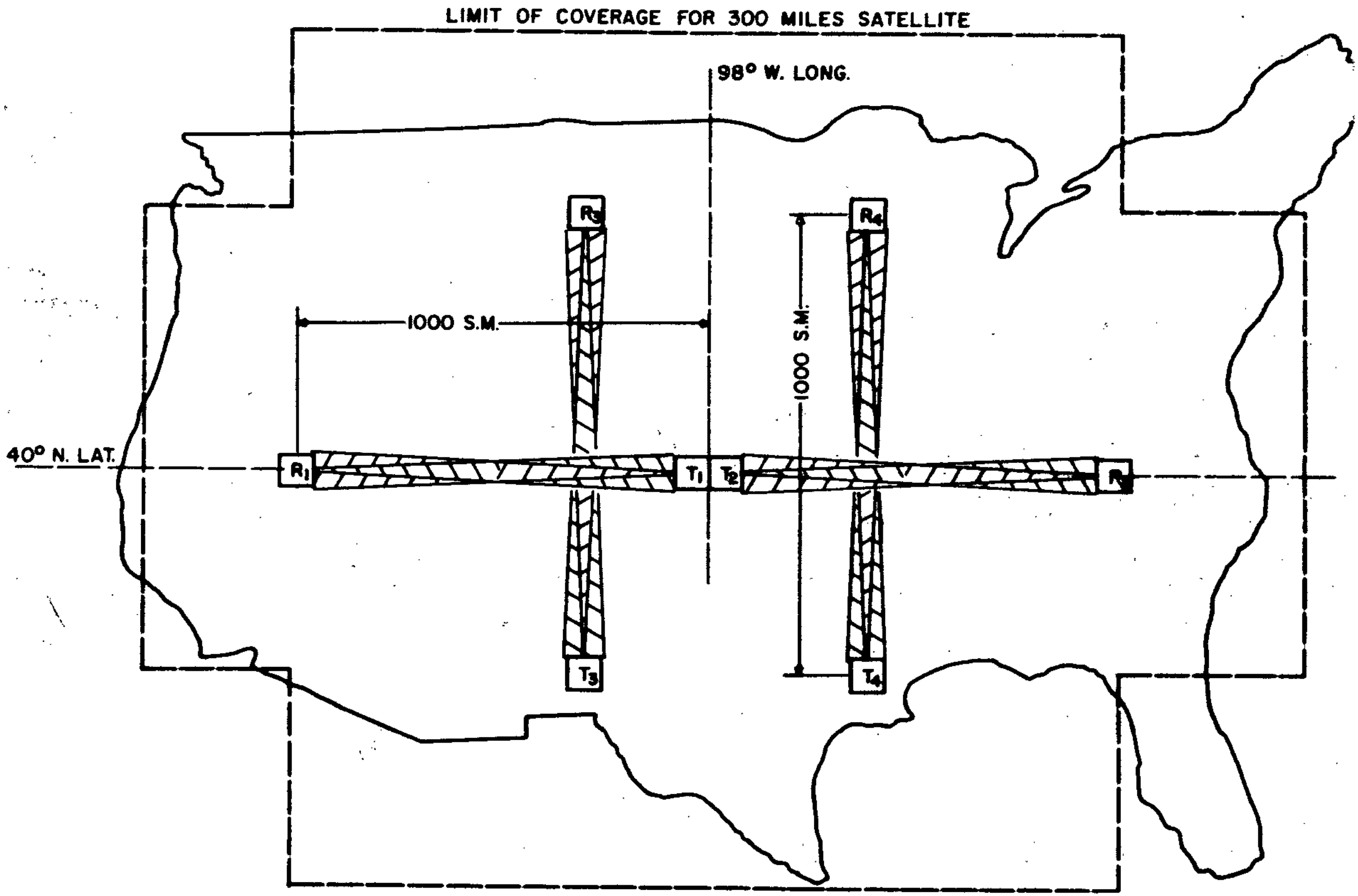


AREA COVERAGE IN PLANE OF FAN BEAMS
FIG. 36



VOLUME COVERAGE OF ONE TRANSMITTER–RECEIVER PAIR

FIG. 37

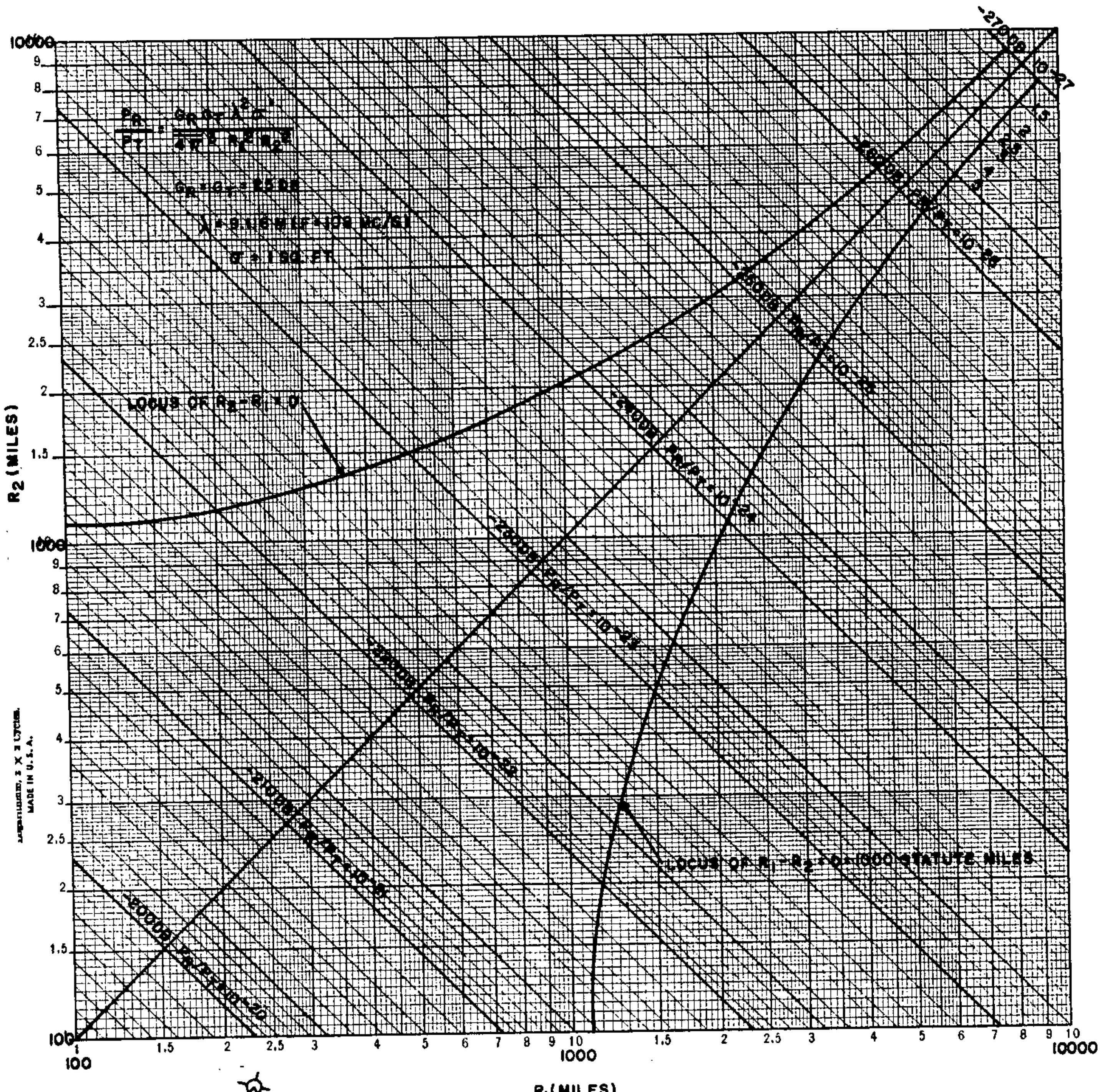


TENTATIVE TRACKING STATION LOCATIONS

FIG. 38

BI-STATIC RADAR

ATTENUATION OR $\frac{P_R}{P_T}$ VS RANGE SUM $(R_1 + R_2)$



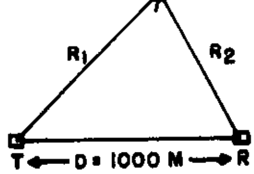


FIGURE 38a

would be located about 1000 miles east and west along the 40 degree latitude circle. In principle, these stations would yield sufficient coverage to permit obtaining enough data from which orbits could be computed. In general only data from one base line would be received for each satellite pass for satellites in near polar orbits and from two base lines for satellites in low inclination orbits. The improvement in strength of the orbit solution and the additional course angle data which could be obtained through the use of additional station pairs with similar nodding antennas, makes it appear desirable to add two (or possibly more) base lines to the network. Error propagation considerations make it desirable to install these base lines at right angles to the original base line. Figure 38 shows base lines R_3 - T_3 and R_4 - T_4 located about 125 miles east and west of the location of transmitters T_1 - T_2. This is not necessarily the optimum location in the east-west direction but is approximately correct. Targets passing through the coverage volume of the system would be intercepted by the nodding beams of one or more transmitter-receiver pairs.

During the time on target interval, $t_T = 0.1$ sec., the system must locate the Doppler frequency in the range of frequencies from 2 kc to 14 kc and measure the frequency to an accuracy determined by the system output signal-to-noise ratio and t_T. The interim DOPLOC automatic lock-on and tracking filter required a minimum of 1.6 seconds to accomplish this sequence of operations. It is thus not adequate for the scanned beam system. The circulating memory filter (CMF) developed for the ORDIR radar by Columbia University is well suited to this application. The CMF will be discussed in more detail under the section of this report devoted to the research program. Other approaches using comb filters were investigated within BRL and an experimental comb filter was developed. This will also be discussed in more detail elsewhere.

1. Transmitter Power Requirements. The total free space attenuation for the bi-static radar case is given by:

$$\frac{P_r}{P_t} = \frac{G_r G_t \lambda^2 \sigma}{(4\pi)^3 R_1^{\,2} R_2^{\,2}} = F(A)$$

$$\text{Attenuation (db)} = 10 \log_{10} \frac{P_r}{P_t}$$

This function is given in Figure 38 a for the case where R_1 and R_2 are the variables and: $G_r = G_t = 25\text{db}$ ($1.4^\circ \times 60^\circ$ beamwidth)

$\lambda = 9.12$ ft (108 mc)

$\sigma = 1$ sq. ft. ($0.1\ M^2$)

In the figure for the case of $R_1 = 2237$ miles and $R_2 = 2450$ miles the ratio: $P_r/P_t = 1.7 \times 10^{-25}$ or $-247\text{db} = F(A)$.

The transmitter power required is given by: $P_t = \frac{P_r}{F(A)}$

The received power required has previously been determined as being 2.8×10^{-19} watts. Hence

$$P_t = \frac{2.8 \times 10^{-19}}{1.7 \times 10^{-25}} = 1.65 \times 10^{6} \text{ watts.}$$

Although this is a high CW power level it can be achieved with state-of-the-art components either by using a multiplicity of power amplifiers, each feeding one or more elements in the transmitter array, or by paralleling several high power transmitter tubes.

V. SCALE MODEL SCANNING BEAM SYSTEM PROPOSAL

The full scale or improved DOPLOC system as proposed first in BRL Memorandum Report No. 1220 is based on the use of the bi-static, continuous wave reflection principle and utilizes for the basic detection and tracking unit a high power radio transmitter and a high gain, narrow-band radio receiver, each coupled to high gain antennas driven through synchronizing equipment. Thin, fan shaped, coplanar beams are scanned about the axis formed by a straight line between the stations to cover a space volume consisting of a half cylinder whose length is equal to the distance between the stations and whose radius is 2000 miles. Computed parameters, based on the radar equation and verified by experience with the interim fence equipment, indicate that this system would detect and track objects having 0.1 m^2 effective cross sectional area over an altitude range of approximately 100 to 2000 miles when a two-million-watt output power is used at the transmitting antenna. Engineering considerations indicated that such a system was feasible with existing state-of-the-art techniques and equipment. The basic cost of such a system, while reasonable in comparison to the cost of other systems of similar proportions, represented a large investment in both funds and engineering effort. Therefore since one of the goals of the reoriented DOPLOC program was the demonstration of the feasibility of the concept of determining orbit parameters by passive continuous wave Doppler techniques, it was proposed to instrument two 700-mile base lines with scaled-down models of the proposed ultimate equipment.

One of the base lines was chosen to utilize the Aberdeen Proving Ground station as the principal research receiving station, using existing equipment augmented with equipment from White Sands Missile Range receiving station. A transmitting station having two 100-KW transmitters and scanning antennas was to be located at Camp Blanding near Jacksonville, Florida. With one antenna beamed toward Aberdeen, Maryland, and one toward Forrest City, Arkansas, two base lines at approximately right angles to each other would provide geometrically strong data for orbit computation and would have permitted utilizing most effectively the technical skill of the BRL personnel without extensive travel and lost time in setting up experiments at remote field

stations. As an alternate location it was proposed that the scale model system of two base lines could be located to fill the gap in the fence in the southeastern section of the United States between Forrest City, Arkansas and WSMR.

The scaled down system would have employed 100-KW radio transmitters, 4 x 40 degree scanning beam antennas, and base lines of approximately 700 miles. Low altitude coverage would have extended down to approximately 125 miles above the surface of the earth, while the high altitude limit would have been about 650 miles. Such a system would have provided adequate detection capability to thoroughly explore the computational and data handling techniques and would have permitted the test and development of any improved techniques found necessary to adopt the DOPLOC concept to the scanning beam methods.

A scanning system of this type would have offered significant improvement over the fixed beam system in detection capability. Instead of relying on having all factors affecting detection suitable during a short period of time that a satellite falls within a severely restricted angular segment of detection volume, this system would have continuously scanned a 160° sector of space volume and have made repeated observations of every object in the scanned volume. With the a priori knowledge that satellites must follow closely the classical laws of orbital motion, the multiplicity of DOPLOC observations on each satellite pass greatly simplifies the problem of distinguishing between satellites and other sources of reflected signals such as meteor trails, aircraft, ionospheric clouds, etc. In addition, it is this multiplicity of observations over a length of arc during a single pass which gives the DOPLOC system the capability of determining orbital parameters without waiting several hours for the satellite to complete one or more revolutions along its orbital path.

A. Request for Contractor Proposals

BRL Specification No. 16-9-59, entitled "Supplemental Information to Oral Briefing Pertaining to Requirements for Scanning Antenna Systems", was prepared and an open briefing was held by BRL and the local procurement

office on 16 September 1959 to acquaint prospective bidders with the requirements of the proposed scaled down DOPLOC system and to solicit bids covering the furnishing and installation of one and two baseline systems as had been proposed to ARPA. The basic bid covered the supplying of the Camp Blanding - Aberdeen base line, less the receiving equipment. This included a prefabricated instrument shelter at Camp Blanding, a transmitter, two scanning beam antennas, and the antenna synchronizing equipment. As an alternate bid, proposals were also requested covering the basic bid, and in addition, a second transmitter housed in the common instrument shelter and two scanning antennas with synchronizing equipment for the Camp Blanding - Forrest City base line. Approximately 25 contractor facilities were represented at the briefing. Twelve proposals, some of which were joint efforts, were received. Prices ranged from less than a million dollars per base line to approximately five million dollars per base line. In general the lowest priced systems proposed using mechanically rotating linear antenna arrays. Other system proposals were based on reflecting type, horn fed antennas scanned by organ pipe scanners, or modified Wullenweber type antennas fed with organ pipe scanners or electronic scanning systems. Several interesting results came from the analysis of the bids received.

Six of the proposals contained antenna designs based on scanning the fan beam by rotating the antenna array structure. Seven proposals contained antenna designs based on stationary antenna structures with the beam scanned by electronic methods. The proposals were requested for two frequencies, 150 mc and 216 mc since these two frequencies had been suggested as possible assignments by the FCC. It was also considered of value to know the cost of the system for what might be considered the lowest and highest practical operational frequencies. At the lower frequency (150 mc) the tracking range is greater for a given antenna power but the antenna size is larger. At the higher frequency (216 mc) the antenna size is reduced by one third but the tracking range is reduced and twice the transmitting power is required compared with that required at 150 mc to maintain a 2000-mile altitude tracking capability. Soon after the contractor briefing the FCC authorized the use of 150.79 mc for DOPLOC dark satellite tracking. Therefore, subsequent

planning was based on the use of the 150.79-mc frequency. It is of interest to note that the 216-mc system antenna and 100-KW transmitter cost estimates were only between five and eight per cent lower than for the 150-mc systems. Considering that increased transmitter power would be required at the higher frequency to obtain the desired range, the higher frequency system would actually be more expensive to install.

During the analysis of the proposals, an important disclosure was made regarding what appears to be a theoretical limit to the use of a circular array or Wullenweber type antenna where the wide dimension of the fan beam must be tilted away from the plane of the array. The effect is that the tilted swept beam degenerates at low elevation angles. When this effect was called to the attention of the contractors who had proposed using a circular scanned array it stimulated a rather extensive theoretical study of this problem. The general conclusion is that for a 4 x 40 degree beam such as was required for the scaled down model the pattern degeneration could be tolerated. However for 1 x 60 degree beams an extreme amount of compensation would be required or the beam would degenerate from a line into a "bow tie" effect which would destroy its low angle coverage. Since one of the conditions of the specification required that the design be capable of scaling up to the two megawatt 1 x 60 degree, 1000-mile base line system, the circular array antenna proposals were excluded from the final consideration. In general these designs were characterized by considerable complexity, high cost and some new component development requirements.

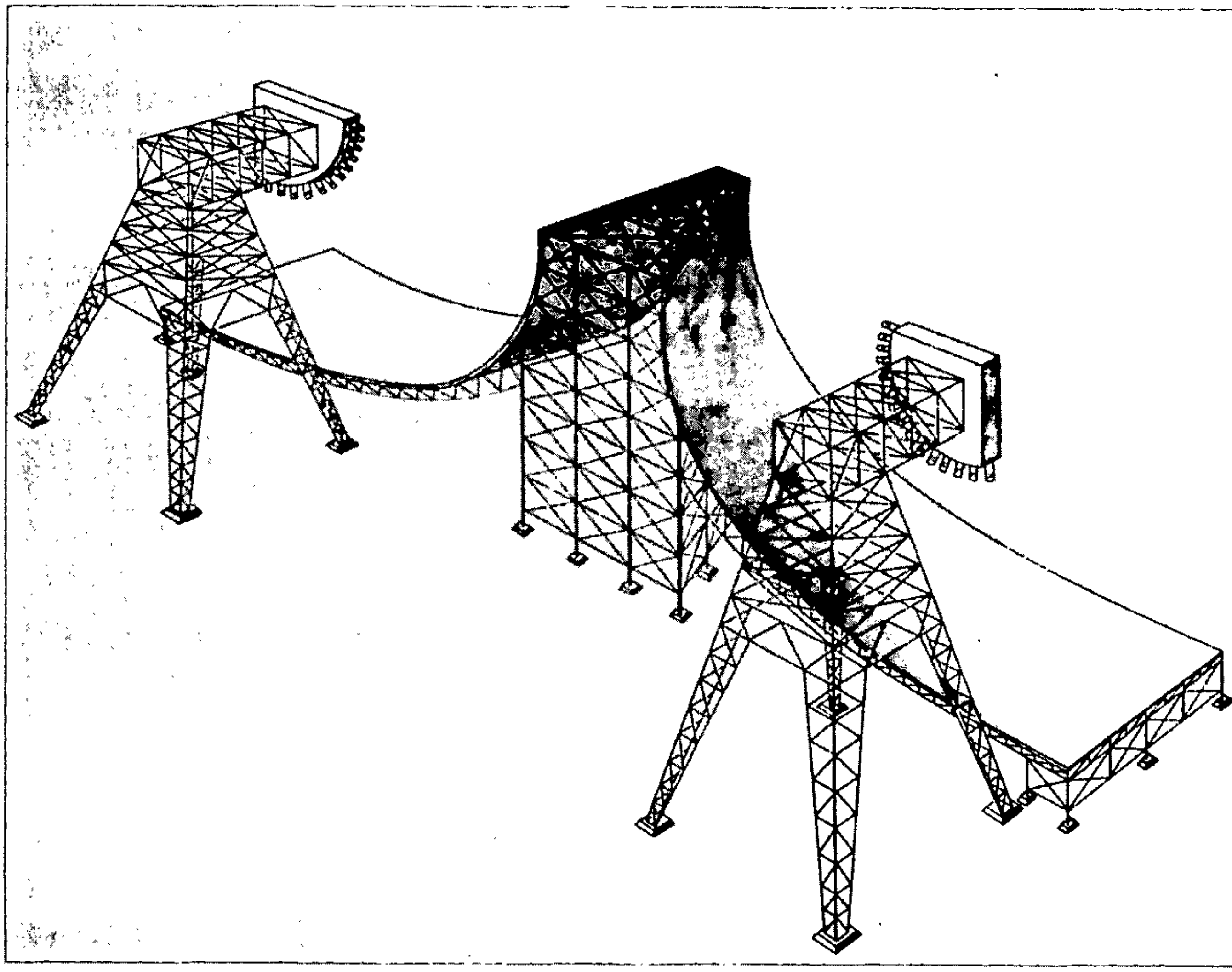
Ultimately, the cost and available funds really determined the choice of antenna system proposed for the scaled down model. The cheapest antenna consisted of a linear array of Yagi antennas mounted on a rotating boom 73 feet in length. Sixteen Yagis, each having seven elements, were used to form the proposed 4 x 40 degree beam. Two arrays, pointed 120 degrees apart, were mounted on the boom to provide continuous scanning of the fan beam with continuous rotation of the boom. One array was to be switched to the feed line when its beam was ten degrees above the horizon, then, after scanning to within 10 degrees of the opposite horizon, it was switched off

and the other array switched on. Four scans per minute, all in the same direction, were to be made by a rotational rate of two revolutions per minute. All polarizations (circular right or left hand and linear vertical or horizontal) were to be provided by the use of crossed Yagi elements. The desired polarization was to be selectable by changing feed connections to the Yagi's.

Synchronization of the transmitting and receiving antenna beams was to be accomplished by a servo motor controlled drive system which was synchronized to a precision frequency standard at each station. Synchronization was to be maintained under winds up to 80 m/hr. There was some question as to whether a rotating boom type of antenna could be scaled up to a 1 x 60 degree beam capable of handling two megawatts of power. One contractor did submit a mechanical design for such an antenna.

A more expensive antenna, but one which seemed more readily adaptable to scaling to the ultimate system requirements consisted of two complex curved surfaces arranged back to back. Each curved surface was illuminated by a set of horns to produce an eighty-degree scan from ten degrees above the horizon to vertical or just beyond vertical. The horns were fed in sequence from an organ pipe scanner. One set of horns and its reflector scanned from 10 degrees above the horizon up to vertical. The power would then be fed to the other set of horns and the scan continued from the vertical down to 10 degrees above the opposite horizon. This constituted a basically new approach where instead of sequentially feeding a large number of radiating elements located on the periphery of a circle, only a relatively small number of elements are fed and the curved reflecting surfaces form the narrow beam. The resultant reduction in complexity is considerable and a much desired degree of versatility is gained in control of beam pattern shape and polarization. Figure 39 shows a drawing of the proposed antenna design.

This reflecting type antenna appears to be the best design for meeting the DOPLOC requirements. The scanner provides accurate angular information relative to the position of the beam once the system has been calibrated. It also has the ability to be scaled to the 1 x 60 degree beam with the two



"THE INFORMATION HEREON IS PROPRIETARY AND THE FACT THAT A PERSON MAY BE GIVEN ACCESS THERETO UNDER GOVERNMENT PROCEDURES IS NOT DEEMED A LICENSE TO USE SAME WITHOUT THE EXPRESS WRITTEN APPROVAL OF MELPAR."

Figure 39 Proposed Antenna Design
Melpar, Inc.

megawatts power handling capabilities. The organ pipe scanner and horn feed system have been designed and tested out in other installations. Therefore the engineering information is available. In view of the larger cost of the horn fed reflecting antenna and the desire to obtain as much information as was practical from the scale model installation, one pair of organ pipe scanned antennas was recommended for the Aberdeen - Camp Blanding base line and one pair of mechanically rotated Yagi arrays was recommended for the Camp Blanding - Forrest City base line. In fact, when the future of the program was in doubt, several research programs ranging in amount of effort from the installation of a single base line in accordance with the lowest priced proposal to two base lines of the scanned reflector antenna system at several times the minimum cost were proposed to ARPA. All of these proposed programs were directed toward arriving at a set of specifications for an ultimate or improved DOPLOC system. As a byproduct of these programs, the application of DOPLOC to the anti-satellite defense problem was to be studied. Although tentative plans were made to install the scaled down base lines and a site was obtained at Camp Blanding, Florida, ARPA did not approve this part of the program. The project was therefore deactivated without field testing the scanning beam concept.

VI. SUPPORTING STUDIES

A. Scanning Antenna Coverage

A study was conducted to determine the number of satellite passes across each of the two proposed base lines, Camp Blanding - Aberdeen and Camp Blanding - Forrest City, and the length of time that the satellite would be in the antenna beam during each pass. This was accomplished by using a map of the United States and representing the 4 x 40 degree antenna patterns as two space volumes, each having a width of 800 miles, a height of 400 miles and a length equal to the distance between the stations. This distance for the Aberdeen - Camp Blanding base line is 730 miles, while the Forrest City - Camp Blanding base line is 610 miles.

Using satellite predictions furnished by Space Track Control Center, each satellite was examined during the period indicated and the total number of passes crossing each base line was recorded. The length of time-in-beam for each pass was calculated utilizing the sub-satellite trace and assuming a nominal satellite velocity of five miles per second. A tabulation of results is shown in Table VI - 1 and a graphical representation is displayed in Figures 40 through 45.

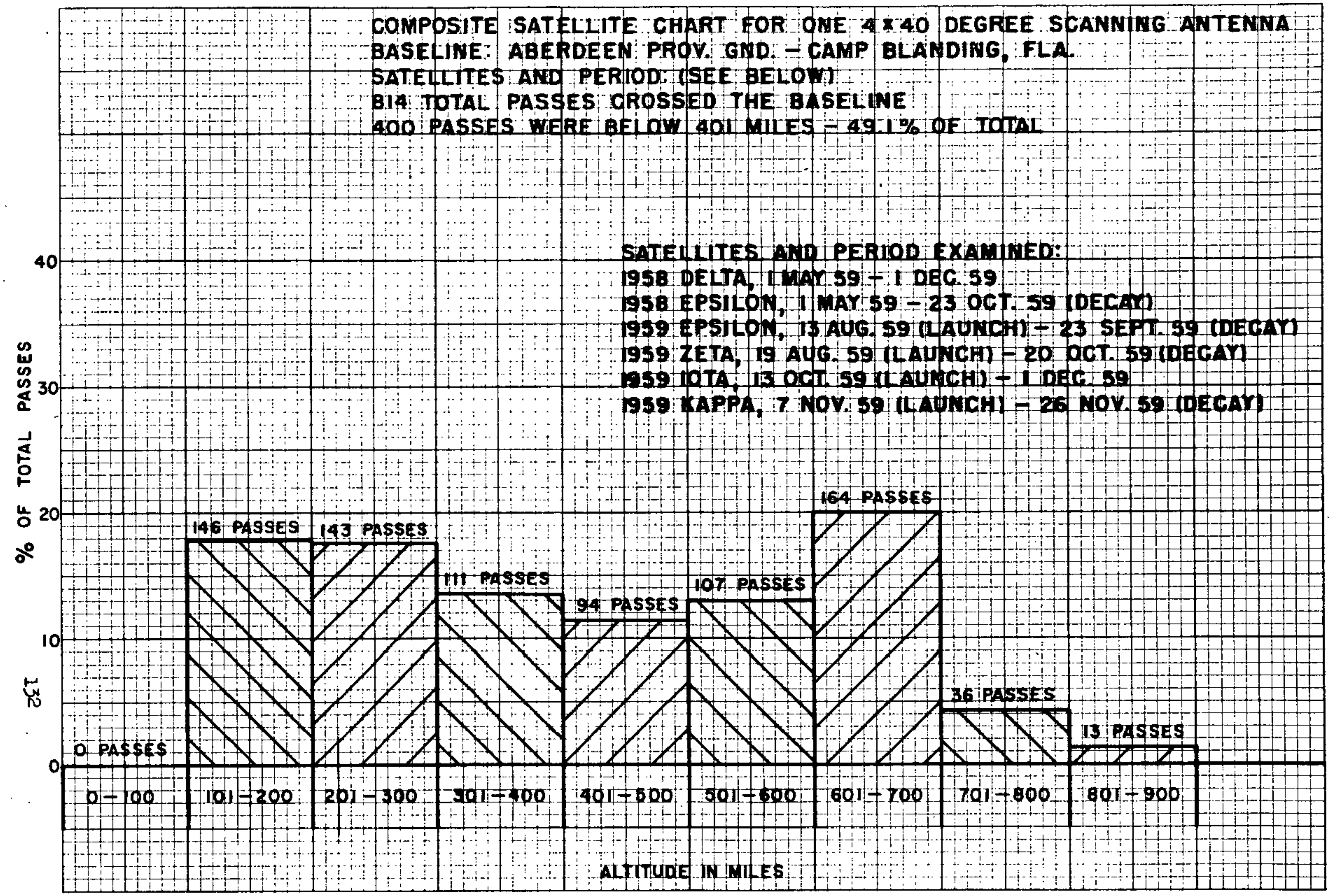

COMPOSITE SATELLITE CHART FOR ONE 4 x 40 DEGREE SCANNING ANTENNA
BASELINE: ABERDEEN PROV. GND. – CAMP BLANDING, FLA.
SATELLITES AND PERIOD: (SEE BELOW)
814 TOTAL PASSES CROSSED THE BASELINE
400 PASSES WERE BELOW 401 MILES – 49.1% OF TOTAL
SATELLITES AND PERIOD EXAMINED:
1958 DELTA, 1 MAY 59 – 1 DEC. 59
1958 EPSILON, 1 MAY 59 – 23 OCT. 59 (DECAY)
1959 EPSILON, 13 AUG. 59 (LAUNCH) – 23 SEPT. 59 (DECAY)
1959 ZETA, 19 AUG. 59 (LAUNCH) – 20 OCT. 59 (DECAY)
1959 IOTA, 13 OCT. 59 (LAUNCH) – 1 DEC. 59
1959 KAPPA, 7 NOV. 59 (LAUNCH) – 26 NOV. 59 (DECAY)
% OF TOTAL PASSES
0
10
20
30
40
0 PASSES
146 PASSES
143 PASSES
111 PASSES
94 PASSES
107 PASSES
164 PASSES
36 PASSES
13 PASSES
0 – 100
101 – 200
201 – 300
301 – 400
401 – 500
501 – 600
601 – 700
701 – 800
801 – 900
ALTITUDE IN MILES

FIG. 40

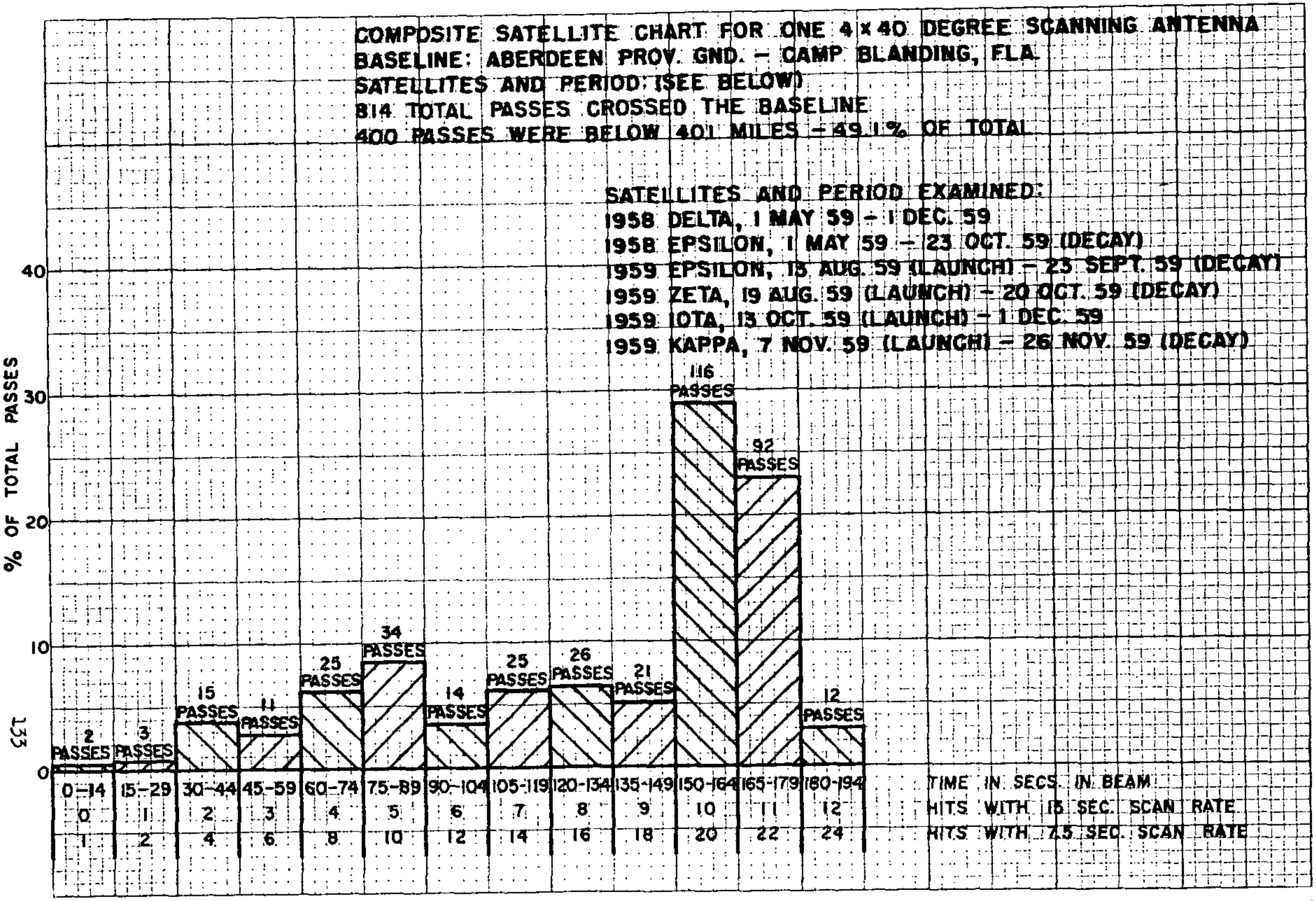

COMPOSITE SATELLITE CHART FOR ONE 4 x 40 DEGREE SCANNING ANTENNA
BASELINE: ABERDEEN PROV. GND. – CAMP BLANDING, FLA.
SATELLITES AND PERIOD: (SEE BELOW)
814 TOTAL PASSES CROSSED THE BASELINE
400 PASSES WERE BELOW 401 MILES – 49.1% OF TOTAL
SATELLITES AND PERIOD EXAMINED:
1958 DELTA, 1 MAY 59 – 1 DEC. 59
1958 EPSILON, 1 MAY 59 – 23 OCT. 59 (DECAY)
1959 EPSILON, 13 AUG. 59 (LAUNCH) – 23 SEPT. 59 (DECAY)
1959 ZETA, 19 AUG. 59 (LAUNCH) – 20 OCT. 59 (DECAY)
1959 IOTA, 13 OCT. 59 (LAUNCH) – 1 DEC. 59
1959 KAPPA, 7 NOV. 59 (LAUNCH) – 26 NOV. 59 (DECAY)
% OF TOTAL PASSES
0
10
20
30
40
2 PASSES
3 PASSES
15 PASSES
11 PASSES
25 PASSES
34 PASSES
14 PASSES
25 PASSES
26 PASSES
21 PASSES
116 PASSES
92 PASSES
12 PASSES
TIME IN SECS. IN BEAM
0–14
15–29
30–44
45–59
60–74
75–89
90–104
105–119
120–134
135–149
150–164
165–179
180–194
HITS WITH 15 SEC. SCAN RATE
0
1
2
3
4
5
6
7
8
9
10
11
12
HITS WITH 7.5 SEC. SCAN RATE
1
2
4
6
8
10
12
14
16
18
20
22
24

FIG. 41

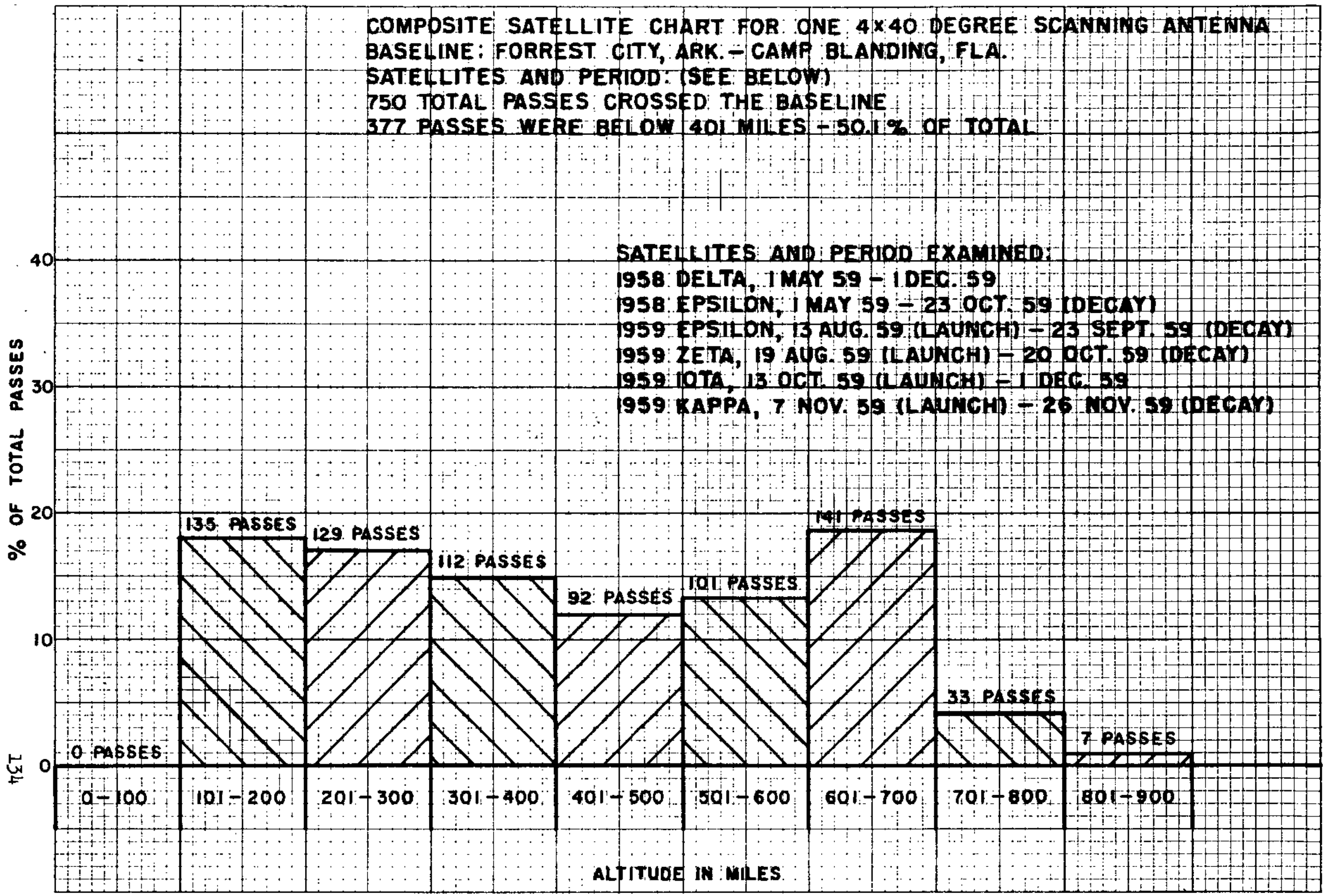

COMPOSITE SATELLITE CHART FOR ONE 4x40 DEGREE SCANNING ANTENNA
BASELINE: FORREST CITY, ARK. – CAMP BLANDING, FLA.
SATELLITES AND PERIOD: (SEE BELOW)
750 TOTAL PASSES CROSSED THE BASELINE
377 PASSES WERE BELOW 401 MILES – 50.1% OF TOTAL
SATELLITES AND PERIOD EXAMINED:
1958 DELTA, 1 MAY 59 – 1 DEC. 59
1958 EPSILON, 1 MAY 59 – 23 OCT. 59 (DECAY)
1959 EPSILON, 13 AUG. 59 (LAUNCH) – 23 SEPT. 59 (DECAY)
1959 ZETA, 19 AUG. 59 (LAUNCH) – 20 OCT. 59 (DECAY)
1959 IOTA, 13 OCT. 59 (LAUNCH) – 1 DEC. 59
1959 KAPPA, 7 NOV. 59 (LAUNCH) – 26 NOV. 59 (DECAY)
% OF TOTAL PASSES
0
10
20
30
40
0 PASSES
135 PASSES
129 PASSES
112 PASSES
92 PASSES
101 PASSES
141 PASSES
33 PASSES
7 PASSES
0 – 100
101 – 200
201 – 300
301 – 400
401 – 500
501 – 600
601 – 700
701 – 800
801 – 900
ALTITUDE IN MILES

FIG. 42

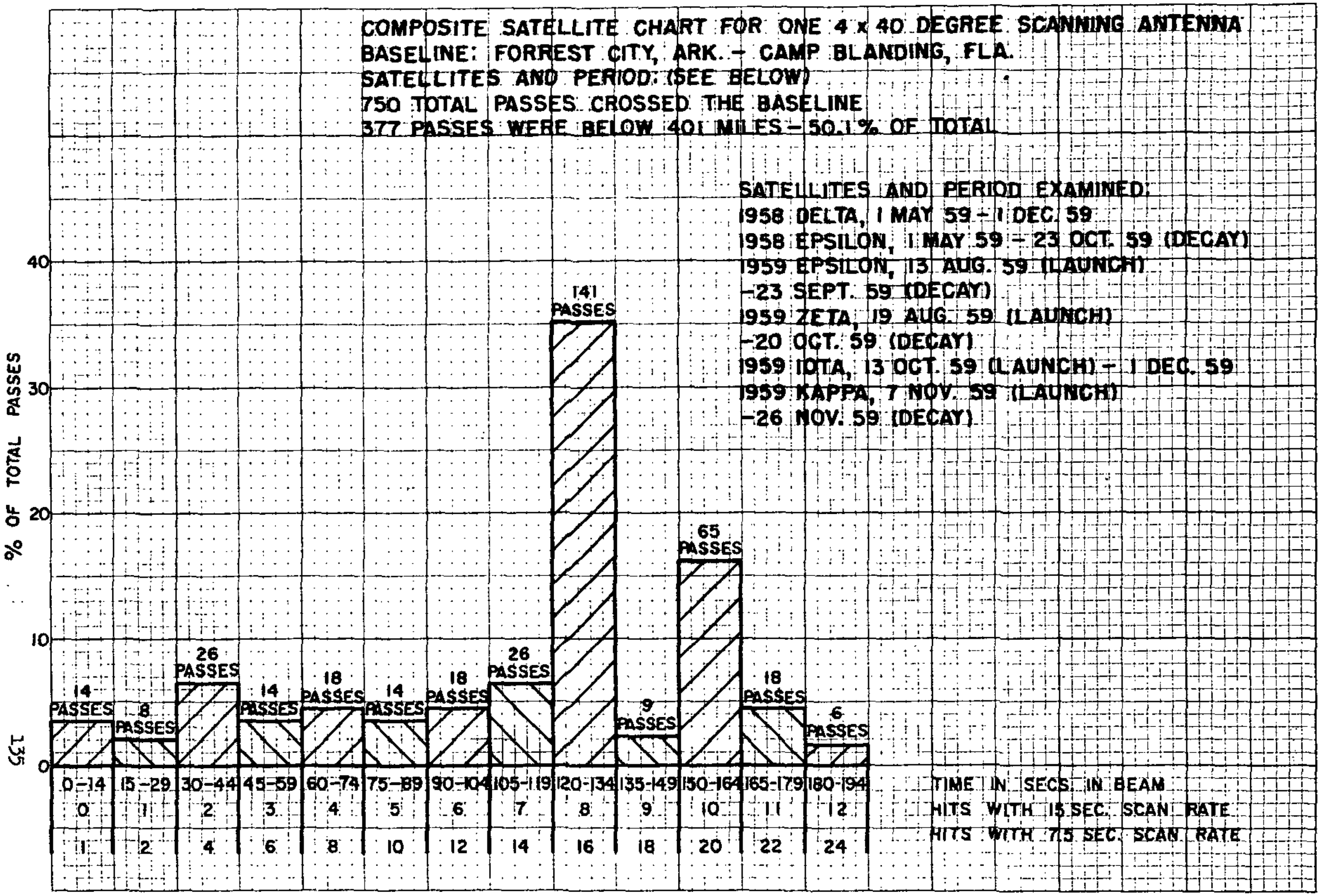

COMPOSITE SATELLITE CHART FOR ONE 4 x 40 DEGREE SCANNING ANTENNA
BASELINE: FORREST CITY, ARK. – CAMP BLANDING, FLA.
SATELLITES AND PERIOD: (SEE BELOW)
750 TOTAL PASSES CROSSED THE BASELINE
377 PASSES WERE BELOW 401 MILES – 50.1% OF TOTAL
SATELLITES AND PERIOD EXAMINED:
1958 DELTA, 1 MAY 59 – 1 DEC. 59
1958 EPSILON, 1 MAY 59 – 23 OCT. 59 (DECAY)
1959 EPSILON, 13 AUG. 59 (LAUNCH)
–23 SEPT. 59 (DECAY)
1959 ZETA, 19 AUG. 59 (LAUNCH)
–20 OCT. 59 (DECAY)
1959 IOTA, 13 OCT. 59 (LAUNCH) – 1 DEC. 59
1959 KAPPA, 7 NOV. 59 (LAUNCH)
–26 NOV. 59 (DECAY)
% OF TOTAL PASSES
0
10
20
30
40
14 PASSES
8 PASSES
26 PASSES
14 PASSES
18 PASSES
14 PASSES
18 PASSES
26 PASSES
141 PASSES
9 PASSES
65 PASSES
18 PASSES
6 PASSES
0–14
15–29
30–44
45–59
60–74
75–89
90–104
105–119
120–134
135–149
150–164
165–179
180–194
TIME IN SECS. IN BEAM
0
1
2
3
4
5
6
7
8
9
10
11
12
HITS WITH 15 SEC. SCAN RATE
1
2
4
6
8
10
12
14
16
18
20
22
24
HITS WITH 7.5 SEC. SCAN RATE

FIG. 43

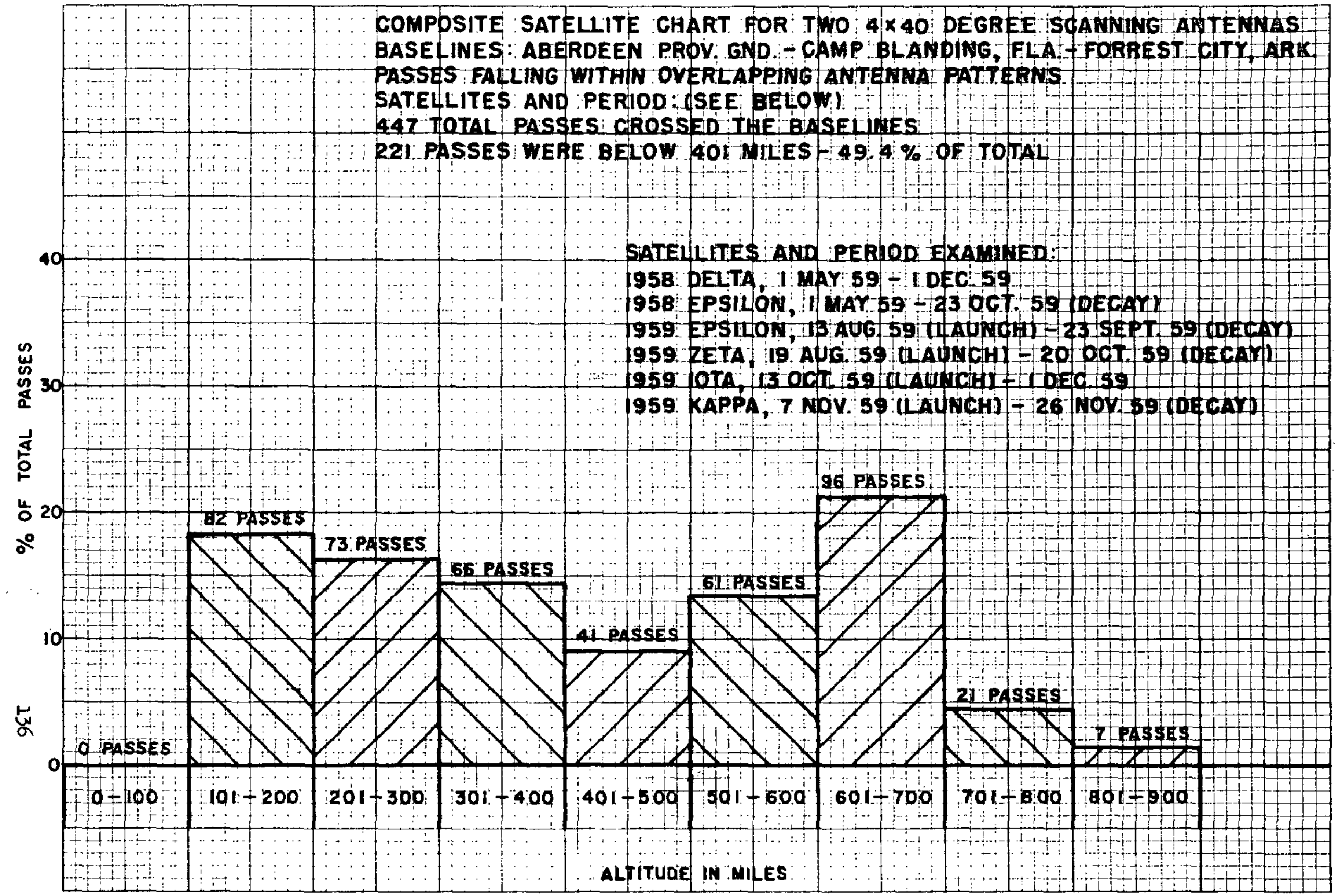

COMPOSITE SATELLITE CHART FOR TWO 4×40 DEGREE SCANNING ANTENNAS
BASELINES: ABERDEEN PROV. GND. – CAMP BLANDING, FLA. – FORREST CITY, ARK.
PASSES FALLING WITHIN OVERLAPPING ANTENNA PATTERNS
SATELLITES AND PERIOD: (SEE BELOW)
447 TOTAL PASSES CROSSED THE BASELINES
221 PASSES WERE BELOW 401 MILES – 49.4 % OF TOTAL
SATELLITES AND PERIOD EXAMINED:
1958 DELTA, 1 MAY 59 – 1 DEC. 59
1958 EPSILON, 1 MAY 59 – 23 OCT. 59 (DECAY)
1959 EPSILON, 13 AUG. 59 (LAUNCH) – 23 SEPT. 59 (DECAY)
1959 ZETA, 19 AUG. 59 (LAUNCH) – 20 OCT. 59 (DECAY)
1959 IOTA, 13 OCT. 59 (LAUNCH) – 1 DEC. 59
1959 KAPPA, 7 NOV. 59 (LAUNCH) – 26 NOV. 59 (DECAY)
% OF TOTAL PASSES
40
30
20
10
0
0 PASSES
82 PASSES
73 PASSES
66 PASSES
41 PASSES
61 PASSES
96 PASSES
21 PASSES
7 PASSES
0 – 100
101 – 200
201 – 300
301 – 400
401 – 500
501 – 600
601 – 700
701 – 800
801 – 900
ALTITUDE IN MILES

FIG. 44

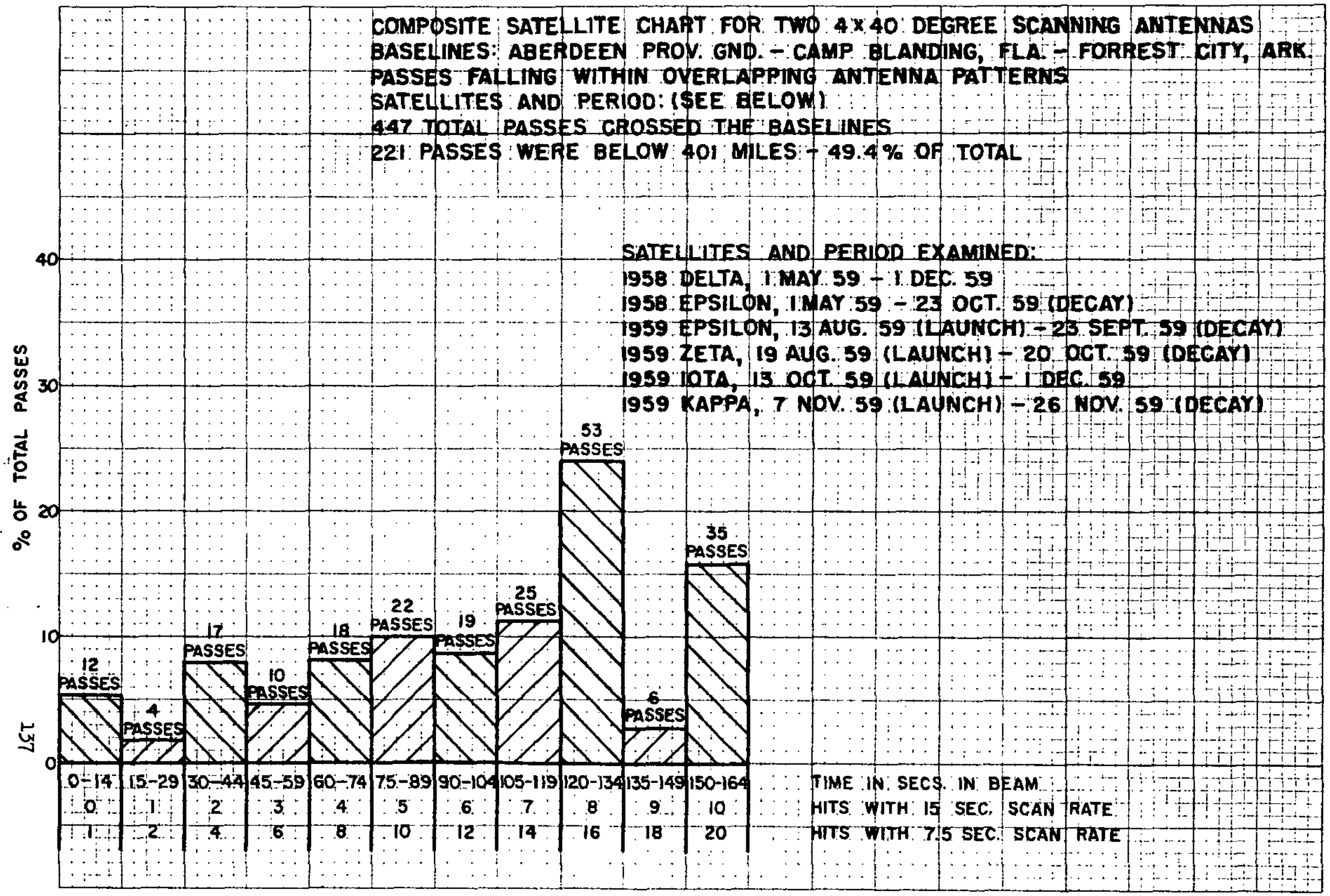

COMPOSITE SATELLITE CHART FOR TWO 4 x 40 DEGREE SCANNING ANTENNAS
BASELINES: ABERDEEN PROV. GND. – CAMP BLANDING, FLA. – FORREST CITY, ARK.
PASSES FALLING WITHIN OVERLAPPING ANTENNA PATTERNS
SATELLITES AND PERIOD: (SEE BELOW)
447 TOTAL PASSES CROSSED THE BASELINES
221 PASSES WERE BELOW 401 MILES – 49.4 % OF TOTAL
SATELLITES AND PERIOD EXAMINED:
1958 DELTA, 1 MAY 59 – 1 DEC. 59
1958 EPSILON, 1 MAY 59 – 23 OCT. 59 (DECAY)
1959 EPSILON, 13 AUG. 59 (LAUNCH) – 23 SEPT. 59 (DECAY)
1959 ZETA, 19 AUG. 59 (LAUNCH) – 20 OCT. 59 (DECAY)
1959 IOTA, 13 OCT. 59 (LAUNCH) – 1 DEC. 59
1959 KAPPA, 7 NOV. 59 (LAUNCH) – 26 NOV. 59 (DECAY)
% OF TOTAL PASSES
0
10
20
30
40
12 PASSES
4 PASSES
17 PASSES
10 PASSES
18 PASSES
22 PASSES
19 PASSES
25 PASSES
53 PASSES
6 PASSES
35 PASSES
0-14 15-29 30-44 45-59 60-74 75-89 90-104 105-119 120-134 135-149 150-164 TIME IN SECS. IN BEAM
0 1 2 3 4 5 6 7 8 9 10 HITS WITH 15 SEC. SCAN RATE
1 2 4 6 8 10 12 14 16 18 20 HITS WITH 7.5 SEC. SCAN RATE

FIG. 45

TABLE VI - 1

1. Base Line

   Aberdeen Proving Ground, Maryland - Camp Blanding, Florida (APG)

   Forrest City, Arkansas - Camp Blanding, Florida (FCY)

   Overlap-Area encompassed by both of above patterns.

2. Satellites and Period Examined

   1958 Delta, 1 May 1959 - 1 December 1959

   1958 Epsilon, 1 May 1959 - 23 October 1959 (Decay)

   1959 Epsilon, 13 August 1959 (Launch) - 23 September 1959 (Decay)

   1959 Zeta, 19 August 1959 (Launch) - 20 October 1959 (Decay)

   1959 Iota, 13 October 1959 - 1 December 1959

   1959 Kappa, 7 November 1959 (Launch) - 26 November 1959 (Decay)

3. Altitude Distribution

	APG	FCY	OVERLAP
Total Passes	814	750	447
Passes Below 401 Miles	400	377	221
Percentage of Total Below 401 Miles	49.1	50.3	49.4

4. Time-In-Beam Distribution

   For APG base line 53.0 % of passes are in the beam from 150 - 179 secs.

   For FCY base line 54.6 % of passes are in the beam from 120 - 164 secs.

   For overlap pattern 39.8 % of passes are in the beam from 120 - 164 secs.

It can be seen from these data that, of the two proposed base lines, the Aberdeen - Camp Blanding base line was the most promising, both from the standpoint of total number of passes and from the time-in-beam of these passes. The long base line accounts for the larger total number of passes, while the geographical location of Aberdeen and Camp Blanding is such that a satellite having an orbital inclination of from 50 to 90 degrees crosses the pattern nearly diagonally and therefore, is within the beam a greater length of time. The data also show that it will be necessary to decrease the antenna scan time from 15 seconds to 7 1/2 seconds per scan to provide 10 - 20 DOPLOC hits per pass for the majority of passes crossing the base line.

B. Cosmic Noise and Interference at 150.79 mc

Following the assignment by the Federal Communication Commission of 150.79 mc for the DOPLOC frequency a study was made of the radio interference occurring over the frequency band of 148 - 153 mc. A standard dipole antenna, a preamplifier, a sensitive receiver and a decibel meter were used in the study. Graphic recordings of signal level were also made. Taxi service dispatch signals were observed at 149 and 153 mc. Except for cosmic and receiver noise the band from 150 - 151 mc was clear. Calibrating the db meter to an arbitrary scale reading of 10 when the preamplifier was terminated with 50 ohms showed a cosmic noise ranging from 0.5 to 1.75 db above the reference point. Starting at 0800 hours local time the noise gradually increased to a peak at around 1200 hours and then decreased toward evening. Using the same equipment and reference point but tuned to 108 mc the noise level ranged from 1.5 to 3 db above the reference with a similar amplitude distribution as a function of time between 0800 and 1630 hours. No local interference was observed except when vehicles passed within about 200 yards of the antenna.

C. Circulating Memory Filter

In order to obtain the maximum benefit of narrow band techniques in the interim system, phase-locked tracking filters were used. These filters were supplied by the Interstate Electronic Corporation, Anaheim, California. The filters were designated Phase Locked Tracking Filter Model IV, and had been developed by Interstate for BRL under a series of research contracts. When the scanning beam antenna concept was developed it became apparent that the time on target would be quite short and that a large amount of data could be generated by multiple targets. Only approximately 0.1 second of time would be available to lock onto a signal and to measure the frequency. This type of performance seemed to be beyond the capability of any type filter which operated on the principle of the Interstate unit.

The Electronics Research Laboratories of Columbia University were known to have developed a frequency estimator using coherent integration detection methods for the ORDIR radar. Contract DA-30-069-509-ORD-2748

was therefore negotiated with Columbia University to cover a study of the applicability of the ORDIR system techniques to the tracking of passive satellites. Final Report No. F/157, No. 14 of the BRL DOPLOC Satellite Fence Series entitled "Summary of The Preliminary Study of the Applicability of the ORDIR System Techniques to the Tracking of Passive Satellites", Columbia University, School of Engineering, resulted from this study. This report contains the results of a study into the problems of coherent integration and frequency estimation in the DOPLOC CW Doppler earth satellite tracking system.

Specifically the report discusses the incorporation of the coherent signal processer known as the Circulating Memory Filter (CMF) into the satellite tracking system. After the parameters of the system are reviewed the theory of operation of the CMF is presented. The coherent integration of signals and the resultant improvement in the signal-to-noise ratio are discussed and the problems involved in distinguishing signals from noise by means of a threshold test are investigated, all with particular reference to the CMF. A technique for estimating the frequency of a sinusoidal input to the CMF and an implementation of the technique are also investigated. Finally the requirements imposed by the CMF on the remainder of the satellite tracking system are discussed. These include requirements for the receiver which furnishes the CMF input and for the data recording, transmitting and processing equipment which makes use of the CMF output.

The detailed specifications for the CMF recommended for use in the satellite tracking system are extracted from the Columbia University report into this report. Also included are specifications for a frequency estimator to accept the CMF output and furnish digital data to a computer and for a receiver which would present acceptable input signals to the CMF. See Section VI - D.

1. The Digital Frequency Readout (DFR). The basic video signal produced in the CMF represents, in analog form, a frequency analysis of the CMF input signal. The time positions of the peaks in the video wave form are measures of the discrete frequencies present in the CMF input signal. The use of a threshold crossing device in the CMF results in a

conversion of the video analog data into a discrete form. More specifically, a pulse will be generated at the instant the video increases above the appropriate threshold and another pulse will be generated at the instant the video decreases below this threshold. Such a pair of pulses will occur for each frequency component present at the CMF input and of sufficient amplitude to exceed the detection threshold.

The object of the DFR is to convert the data (frequency) pulses at the output of the CMF unit into binary numbers which represent the unknown frequencies. One method of accomplishing this is shown in Figure 46. Entering on the left of this figure is the output of the CMF unit. For the purpose of this explanation, it is assumed that three unknown frequencies are present and all of these will be read out.

The first pulse of a pair of calibrate pulses causes the train of clock pulses to appear at lines 1a, 2a and 3a at the respective outputs of the logic blocks. These pulse trains are applied through binary stages (flip-flops) to the counters in sections 1, 2 and 3. The second calibrate pulse causes the train of clock pulses at lines 1a, 2a and 3a to be shifted to lines 1b, 2b and 3b, respectively, thereby bypassing the binary stages. The effect of this is to divide the number of clock pulses existing between the pair of calibrate pulses by two. Hence any count registered later on a counter will indicate the number of clock pulses occurring from the average time instant between the calibrate pulses to the instant when the counter was stopped. The average time between threshold crossings is a good measure of the applied frequency since this method estimates the time of occurrence of the peak in the video signal. After the second calibrate pulse has occurred, then, the clock pulses are entering all three counters along lines 1b, 2b and 3b, respectively. When the first data pulse of the first pair of data pulses occurs, the clock pulses are switched so that the counter is counting at half its previous rate. The second pulse of the first pair of data pulses causes the counter of section 1 to stop. The count thereby registered is the number of clock pulses between the center of the calibration pulses and the center of the first pair of data pulses.

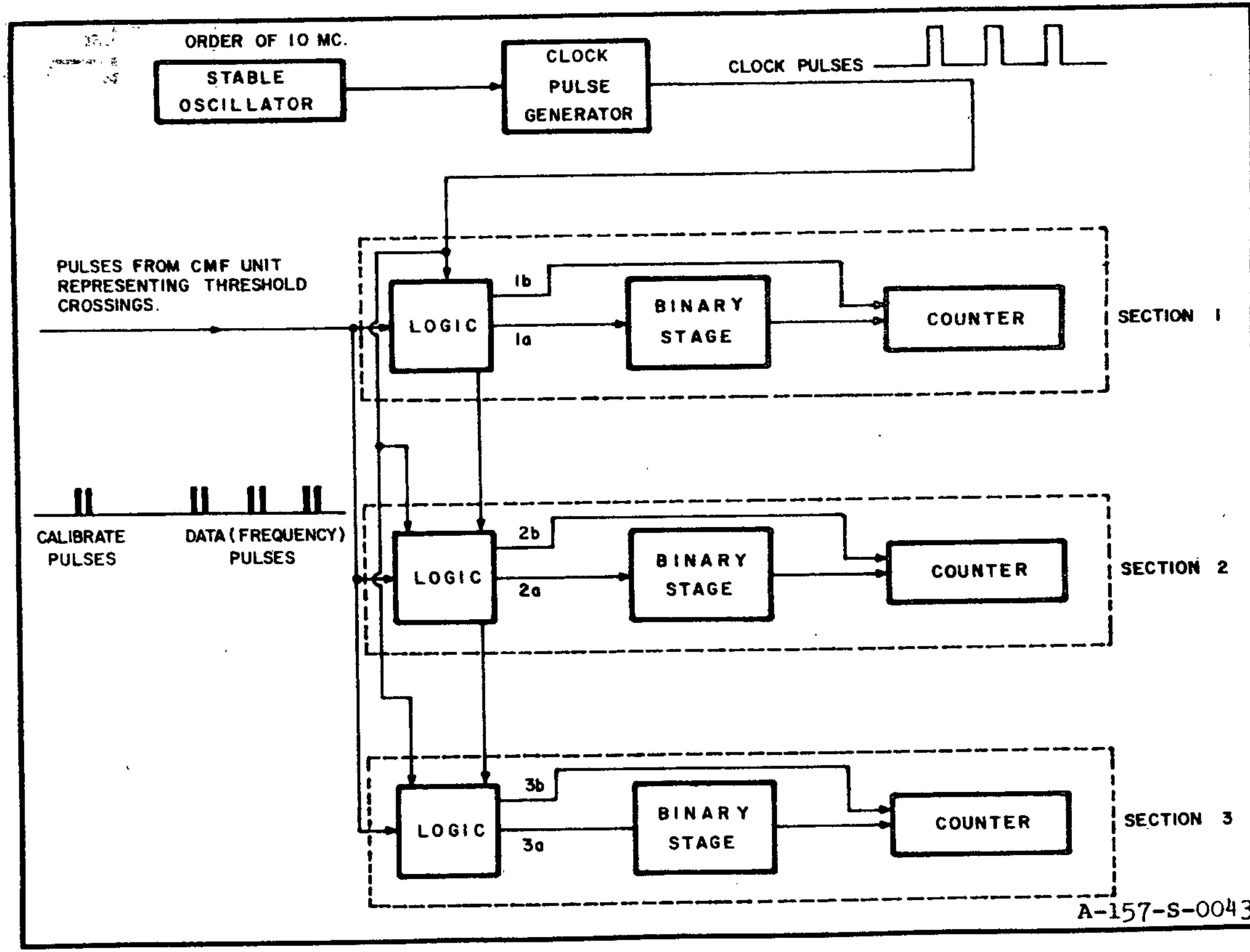


Fig. 46 An Implementation for the DFR

When the counter of section 1 is stopped, the logic unit of section 1 sends a signal to the logic unit of section 2 in order to prepare it for responding to the next pair of data pulses. The second pair of data pulses then causes a count to be registered on the counter of section 2 in a manner similar to that described above. The third pair of data pulses causes the counter of section 3 to stop.

A clock pulse rate of about 10 mc is reasonable since this has a period of 0.1 μs, which corresponds to a frequency quantization of about 2 cps (using the conversion factor of 20 cps/μs). If a 10-mc clock rate were used, the maximum count possible in 1 ms is 10,000. This requires a 14 bit register. The implementation presented here is only one of a number of possibilities and is given as an illustration of the general nature of the implementation problem.

2. <u>Digital Data Recording and Data Rates for CMF</u>. In this study it was assumed that the following data would be recorded whenever a "frequency readout" occurred:

a. Time (of occurrence of a frequency readout).

b. Antenna beam elevation angle.

c. Echo frequency count (up to three counts).

To determine the average data transmission rate it was assumed that:

1. On every scan of the antenna beam, one target readout occurs.
2. On every scan of the antenna beam, one meteor echo is observed.
3. The meteor and target readouts do not occur simultaneously.

Based on a reasonable false alarm probability, the data rate derived has an average rate of about 18 hits per second. As an indication of channel capacity, a 7-channel teletype operating at 65 words per minute has a capacity of about 18 hits per second. Thus the recording rate required was not found to be excessive.

3. <u>CMF DOPLOC Receiver Specifications.</u>

a. Receiver Bandwidths. The receiver pre-detection bandwidth should be large enough to accommodate the 24 kc Doppler frequency range, but not so large as to enable extraneous echoes to be processed. Although the CMF

provides large rejections for signals outside of its 12-kc input frequency range, such signals might produce undesirable inter-modulations or cause temporary saturation of the CMF input circuitry. A 1 db pre-detection bandwidth which is no larger than 20 kc and no smaller than 15 kc was specified for the i.f. stage which feeds the CMF. The receiver pre-detection band pass characteristics must be maintained flat over the entire 24-kc Doppler frequency range. Since, the CMF rejection characteristics are specified to be flat to $\pm$ 1 db (maximum) within its 12-kc frequency coverage, the receiver characteristics should be roughly $\pm$ .1 db to prevent further deterioration.

b. Frequency Scan. The receiver will scan the twenty-four kc Doppler frequency range in two steps (12 kc per stage). Each frequency scan will be actuated by a command pulse which is generated by the CMF at the termination of its integration period.

c. Dynamic Range. The receiver must meet the following dynamic range specifications:

1. For a noise free, sinusoidal input voltage of amplitude 55 db* rms at any frequency in the 24-kc frequency coverage, all receiver output spurious responses shall be more than 40 db (with respect to the input) below the output peak response.

2. For a noise free input signal consisting of two sinusoids each of amplitude, 55 db rms and at different frequencies within the 24-kc coverage all receiver output spurious responses shall be more than 40 db (with respect to the input) below the output peak response. Spurious responses generated in the receiver outside the 1 kc channel containing the signal must be kept 55 db below the signal peak.

d. Receiver Gain and Voltage Levels. As a compromise between CMF and AGC requirements and loss in detectability due to the addition of CMF and receiver noise, the receiver gain was set at such a level that the sum of the CMF and receiver noise would attain a level of about 11db. This corresponds to a loss in detectability of about 0.4 db and to a maximum CMF AGC requirement of about 15 db, that is, to a maximum signal of about 70 db.

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* The db values quoted are relative to the usual reference level of CMF internal noise referred to the CMF input.

e. Timing Pulses and Auxiliary Outputs. The receiver must also supply (in binary form) all remaining information not supplied by the CMF that is either necessary for computing purposes (receiver oscillator settings, absolute time, etc) or desirable to record (gain settings, antenna positions etc).

f. Automatic Noise Level Control. During the antenna scan period, cosmic noise fluctuations may cause the receiver noise level to vary by several db. Such fluctuations could cause a large increase in the system false alarm probability and might therefore result in a temporary saturation of the data transmission equipment. To control these fluctuations an automatic level control technique which changes the gain setting only when changes in the noise level have occurred is required. A parallel control scheme with the following design factors is recommended:

1. An accurately calibrated receiver gain bias characteristic of sufficient dynamic range to allow correction for anticipated input noise variations.

2. A gain stability in both the receiver and estimator channels sufficient to maintain the above calibration.

The overall response of the DOPLOC receiver shall be such as to supply the following to the input of the Circulating Memory Filter:

1. Carrier Frequency - 11 mc.
2. Bandwidth (1 db points). No larger than 20 kc and no smaller than 15 kc.
3. RMS Voltage Levels. 11 mv $\pm$ 1 mv minimum detectable signal, 560 mv $\pm$ 6 mv maximum processed signal to 4 volts maximum output signal.
4. Receiver Gain. The receiver shall have a gain such that the rms value of its output noise (after AGC) shall be nominally 3.6 mv $\pm$ 0.5 mv in a 10-cps band.
5. Receiver Noise AGC. The receiver shall have a noise actuated AGC such that the receiver output noise remains constant to within $\pm$ 6.2 db.

6. Frequency Stability. All local oscillators shall have a stability or be so recorded that the output frequency uncertainty is less than 2 cps (standard deviation) and 2 cps mean.

7. Output Resistance. 100 ohms to feed the 100 ohm input resistance of the CMF.

8. Frequency Scan. The DOPLOC receiver shall scan the 24-kc expected frequency range in two steps (12 kc per step).

9. Timing Pulses. The DOPLOC receiver shall supply "Integrate Start" pulses to the CMF at a prf of 10 per sec. These shall be positive pulses and shall have amplitudes of at least 5 volts, into a 100-ohm load, rise and fall times (10 per cent to 90 per cent of peak amplitude) of not more than 1/2 μsec., and duration (between 90 per cent points) of not less than 1 μsec nor more than 3 μsec.

D. Circulating Memory Filter Specification

The following specification is extracted from Columbia University Report "Summary of the Preliminary Study of the Applicability of the ORDIR System Techniques to the Tracking of Passive Satellites", 11 February 1960, Appendix B. These specifications are quoted here because they do not otherwise appear in a BRL report. Readers not interested in detail of the CMF specification are advised to omit this section.

1. Spectrum to be Analyzed (Frequency Coverage):

$$10{,}994.0 \begin{cases} +1.0 \\ \\ -0.0 \end{cases} \quad \text{to} \quad 11{,}006.0 \begin{cases} +1.0 \\ \\ -0.0 \text{ kcps} \end{cases}$$

2. Input Resistance. 100 ± 2 ohms

3. Effective Input Noise Voltage. The noise generated by the CMF shall be such that if a 1.0 mv rms noise voltage per 10-cps bandwidth is applied to the input, the output noise shall increase by no less than 3 db. The nominal value of effective input noise (self-generated) equal to 1 mv rms per 10-cps bandwidth is thus defined. All subsequent voltage levels shall be expressed in db above 1 mv (CMF noise in 10-cps bandwidth is at 0.0 db).

4. Nominal RMS input Signal Levels. (db above CMF noise in a 10 cps band)

a. Receiver plus CMF noise per 10 cps band 11.0

b. Receiver noise per 12 kcs band 41.8

c. Minimum detectable signal 21.4

d. Maximum (unlimited) signal 70.0

5. Nominal Coherent Integration Time. Variable from 20 msec to 110 msec in approximately 1 msec steps. All specifications shall be met after integrating during a nominal integration time of 93 msec.

6. Integration Start. The CMF shall begin to integrate an input voltage not more than 1.0 ms after receiving an integrate start pulse.* This pulse will have the following characteristics:

a. polarity: positive

b. amplitude: 5 volts or greater across 100 ohms

c. duration: between 1 and 3 μsec

d. risetime: 0.5 μsec (10 per cent to 90 per cent)

e. period: nominally one pulse every 100 ms.

The repetition rate acceptable to the CMF shall be from 9 pulses per sec to 40 pulses per sec.

7. Dead Time. The nominal dead time shall be within 1 msec of the difference between the input pulse period and the set integration time but shall never be allowed to become smaller than 4 msec.

8. Linear Operating Range. For any single sinusoidal, noise free input signal within the frequency coverage, having an rms amplitude between 16 db and 36 db there shall exist a linear relation between rms input voltage amplitude and peak video output voltage. Linearity is here defined to be within 5 per cent for the best linear fit.

9. Frequency Coverage Ripple. For an input sinusoid of constant amplitude between 16 db and 36 db, the CMF video output shall be constant to within ± 1 db for all input frequencies within the frequency coverage.

* Externally supplied

10. Selectivity. For a sinusoidal, noise free input signal at any frequency within the frequency coverage and of amplitude no greater than 55 db and no less than 16 db, the output selectivity shall be as shown in Figure 47. All side lobe responses must be at least 40 db below the effective peak response for all inputs up to 55 db. All specifications pertain to that part of the characteristics which lies below 36 db (linear operating range).

11. Signal Enhancement. The selectivity characteristic as specified shall be obtained without causing the signal enhancement to fall more than 1.7 db below that obtainable from an ideal coherent integrator, for an input signal not more than 30 db.

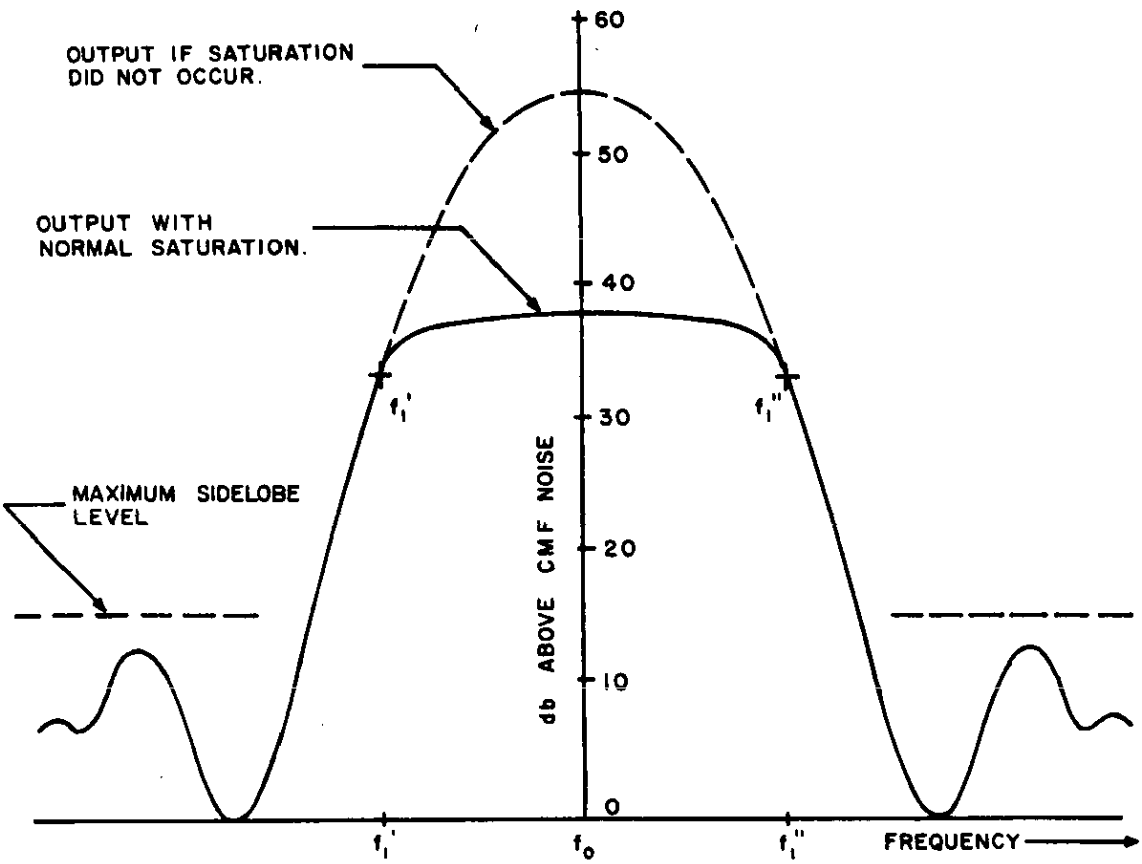
12. Spurious Response Levels.

a. For a noise free, sinusoidal input voltage of amplitude 55 db rms at any frequency in the frequency coverage, all output spurious responses shall be more than 40 db (with respect to the input) below the output peak response.

b. For a noise free input signal consisting of two sinusoids each of amplitude 55 db rms and at different arbitrary frequencies within the coverage, all spurious responses shall be more than 30 db below the main responses (with respect to the input). This voltage level shall be called the dynamic processing limit.

13. Signal Limiting AGC. The CMF shall supply a signal limiting AGC which does not significantly deteriorate the specified selectivity characteristic and spurious response levels (items 9 - 12). There shall be an independent AGC for each time multiplexed channel. Each AGC shall be designed so as to meet the minimum specifications shown in Figure 48. In this figure, both the input to the AGC and its output have been normalized with respect to the input terminals of the CMF. The absolute gain and signal levels that are processed by the AGC shall be chosen so as to best compliment CMF design. The salient features of the AGC are:

a. For all inputs between 10 and 40 db the output-input characteristic shall be linear to within 5 per cent (best linear fit).



$$f_1 = f_1' - f_1''$$

$$\Delta f = \frac{f_1' + f_1''}{2} - f_0$$

DB BELOW EFFECTIVE (UNSATURATED) PEAK	MAXIMUM FREQUENCY SPREAD f_1 CPS	MAXIMUM ASYMMETRY Δf CPS
0	0	0
-1	8.5	± 1.0
-2	13.0	± 1.5
-3	17.0	± 1.5
-6	21.5	± 2.0
-10	28.0	± 2.0
-15	32.0	± 2.5
-20	37.5	± 3.0

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Fig. 47 Typical CMF Response to a Maximum Amplitude Sinewave (with Time Weighting)

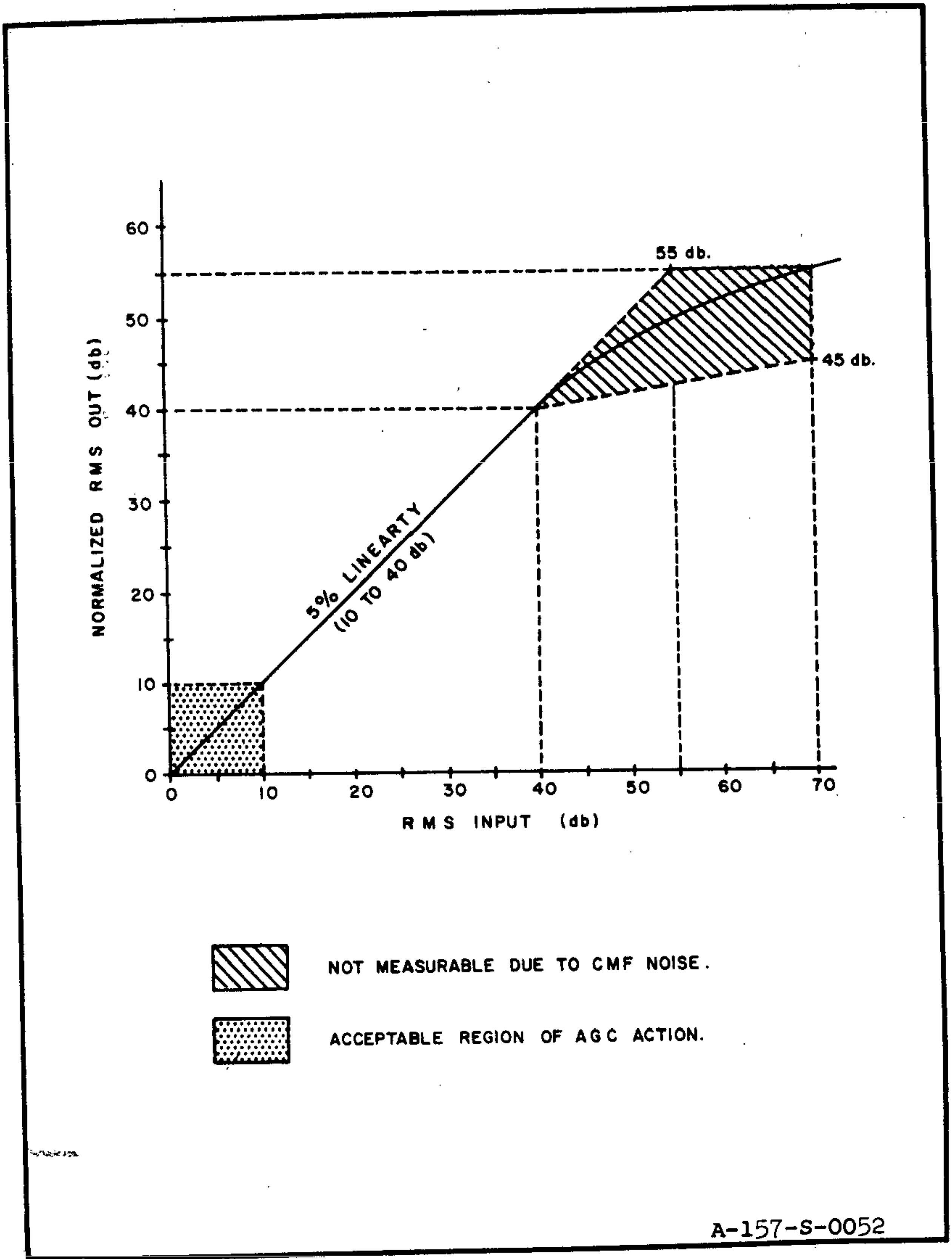

Fig. 48 Signal AGC Requirements

b. For all inputs between 40 and 70 db there is an acceptable region of AGC action as shown in Figure 48 but under no circumstances shall the output exceed 55 db for all input signals up to 70 db.

c. For all inputs below 10 db the AGC output should be such as to not degrade system performance.

d. The AGC gain must be reset at least once during each integration time for each multiplexed channel i.e., it need not be continuously in operation during the integration time.

14. Video Outputs. The last circulation time of the integration time shall be called the display period. The thirteen* time intervals during the display period which contain the thirteen time multiplexed channels shall be called the channel display times. The following video outputs with appropriate oscilloscope synchronizing pulses shall be provided by the CMF:

a. Entire integration time.

b. Gated video during display period.

c. Gated video during each channel display time.

All video outputs shall have an amplitude of at least 40 db peak into 100 ohms for a noise free input signal of 20 db.

15. Display Period Start. A synchronizing pulse shall be provided to indicate the start of the display period. This pulse shall occur approximately 1 μsec before the beginning of the display period and shall have the electrical characteristics specified for the timing pulses described in Section 6.

16. Threshold Levels and Stability. The CMF shall provide a video threshold which shall be continuously variable from 15 to 35 db with a drift of less than ± 0.2 db during any time interval no shorter than 0.1 sec. and no longer than the time between calibrations. The nominal threshold level shall be 24.4 db.

This threshold shall operate on all video output signals which result from input signals less than 40 db. For video output signals which result from input signals greater than 40 db, this threshold shall operate on the video after it has been attenuated by 10 db. This operation shall be automatic.

* Twelve signal channels and one calibration channel

17. Output Data Pulses. Each time during the display period that the video output of the CMF is increasing and is equal to the threshold described in Section 16 the CMF shall produce a pulse. The time occurrence* of this pulse shall have a mean value within 0.05 μsec of the time that the threshold is equal to the video output and shall have a standard deviation of not more than 0.1 μsec. These pulses shall be positive and have an amplitude of at least 2 volts, rise and fall times (10 per cent to 90 per cent of peak amplitude) of no more than 0.05 μsec, and a duration (between 90 per cent points) of not more than 3 μsec nor less than 0.2 μsec.

Each time during the display period that the video output is decreasing and is equal to the threshold described in Section 16 above, the CMF shall produce a pulse. The time of occurrence of this pulse shall have a mean value within 0.05 μsec of the time that the threshold is equal to the video output and shall have a standard deviation of not more than 0.1 μsec. The electrical characteristics of these pulses shall be the same as those for the data pulses described above.

The pulses marking the positive going threshold crossings shall be provided at a separate output terminal from the pulses marking the negative going threshold crossings.

18. Output Impedance Levels. All video outputs, synchronizing pulses, and output data pulses shall be capable of driving 100 ohm impedances.

19. External Terminals.

a. Chassis ground

b. Display period synchronizing pulse

c. Output data pulses (two terminals as provided in Section 17)

d. AGC voltages

e. External time weighting function generator with disconnect for built-in time weighting function

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* The time of occurrence of the data output pulses shall be measured with respect to pulses originating from the calibration signal contained in the calibration display channel. The time of occurrence specifications shall apply to all input signals of amplitude between 21.4 db and 55 db and a threshold setting of 24.4 db.

f. All necessary monitoring functions for alignment and operation as determined by the contractor.

20. Acceptance Tests. All items specified shall be checked for conformity with the specifications in the presence of BRL representatives and a reliability run shall be made such that the equipment shall be observed to operate satisfactorily for five consecutive days at eight hours per day. During this five-day period, preventative maintenance and check-out shall be allowed during the period in which the equipment is turned off.

21. CMF Information Available. The contractor shall supply an instruction report sufficiently comprehensive to allow an engineer to perform preventative maintenance and generally service the equipment. The report shall cover theory of operation of the equipment, block diagrams, detailed circuit diagrams, checkout and preventative maintenance procedures, servicing of breakdowns, etc.

22. Installation. Installation and initial checkout of the equipment at the radar site shall be supervised by a contractor representative.

23. Power Requirements. The equipment shall operate from any constant frequency constant amplitude power source whose rms amplitude is greater than 105 volts but less than 120 volts and whose frequency is greater than 50 cps but less than 65 cps.

E. Studies Relative to DOPLOC Receivers

1. BRL Report No. 1093, "The Dynamic Characteristics of Phase Lock Receivers" by K. A. Pullen. The first receivers used in detecting satellite signals were commercial versions of the R-390 A/URR as sold by Collins Radio Company under the model number J-51. These receivers were used to receive the signals from the first Russian Sputniks. The same receivers along with type R-390A/URR were later used for the interim DOPLOC stations. Since these receivers would not tune above 32 mc modified Tape-Tone converters were used to operate at 108 mc. These circuits were improved through the use of very stable frequency standards and frequency synthesizers as heterodyning frequency sources. Except for some preamplifiers and special

mixing circuits the interim DOPLOC receiving equipment used essentially off-the-shelf items. The phase locked tracking filters were built to specifications but early models were available when satellites became a reality.

With the development of the concept of scanning beam antennas for the DOPLOC system, it became obvious that more sophisticated receivers would be required. The first study made resulted in BRL Report No. 1093, January 1960, entitled "The Dynamic Characteristics of Phase-Lock Receivers", by Keats A. Pullen, Jr. This was Report No. 8 in the ARPA Satellite Fence Series. The report treats of the general theory of phase locked circuits as applied to small amplitude signal detection. Except for the following conclusions relative to the receiver, the reader is referred to the original report.

a. "Constant sensitivity to phase changes requires the use of a phase detector in the signal circuit and a cross correlation type detector in the gain control circuit, so that the gain action is controlled by the desired signal alone and not the signal and noise together."

b. "The limitation of phase error requires either the use of a common i.f. system for a pair of signals or the use of considerable local feedback on all of the r.f. and i.f. amplifiers. The use of a circuit without local feedback around the i.f. amplifiers does not introduce phase stabilization; it only introduces a compensating phase into the feedback path. Since the phase of the signal in the feedback path is used as a measure of the received phase, no removal of internal phase errors results unless local feedback over the individual stages is used."

c. "Adjustment of the phase-lock loop for minimum position, velocity, and acceleration error requires the use of a rather different type of circuitry than has been used in general in this type of equipment. The presence of frequency compensating circuits between the phase detector and the reactance modulator introduces neither position nor velocity error correction, but contributes only to the correction of the acceleration error. Correction for position and velocity error must be accomplished in the feedback loop."

d. "The introduction of full correction for velocity error requires the use of a phase network in the feedback path of rather unusual characteristics. Further investigation of this portion of the circuit appears to be justified."

2. DOPLOC Receiver Design for CMF. BRL Technical Note No. 1345, August 1960 entitled "The DOPLOC Receiver for Use with the Circulating Memory Filter " by Kenneth H. Patterson. Report No. 18 in the ARPA Satellite Fence Series, discusses a radio receiver which was proposed for use with the Circulating Memory Filter. Figure 49 is a schematic block diagram of this receiver. Basically it consists of an r.f. amplifier operating at 150.79 mc and three i.f. amplifiers with automatic gain control and the stabliized mixer frequency sources. The 1st, 2nd and 3rd i.f. amplifiers operate at 19.217296, 2.770708 and 10.994002 mc respectively. The receiver provides the specified 11 mc signal output to the circulating memory filter. The required frequency stability is provided by bringing the required mixer frequencies from frequency standards and synthesizers. The receiver also supplies to the filter the "start integrate" pulses. For a more detailed discussion reference is made to the above mentioned report.

3. Tests of Parametric Pre-amplifiers. BRL Technical Note No. 1354, October 1960 entitled "Parametric Pre-Amplifier Results" by K. H. Patterson. Report No. 19 , ARPA Satellite Fence Series describes the results of a series of tests with some parametric amplifiers supplied by Microwave Associates, Inc. These amplifiers were rather simple in so far as physical construction was concerned. They consisted of a coaxial cavity with an injection and a pickup loop. The 50-ohm loops appeared to be identical. Each was provided with a standard type N coaxial cable fitting. A coarse and fine tuning adjustment were provided. The latter was actually a modified micrometer mechanism. Provision was also made for mounting a varactor diode and an adjustment to vary a capacitor connected in series with the diode.

First results with the parametric amplifiers were very disappointing. It was then discovered that the recommended pump frequency was the wrong value for the amplifiers. Later laboratory tests showed the amplifiers

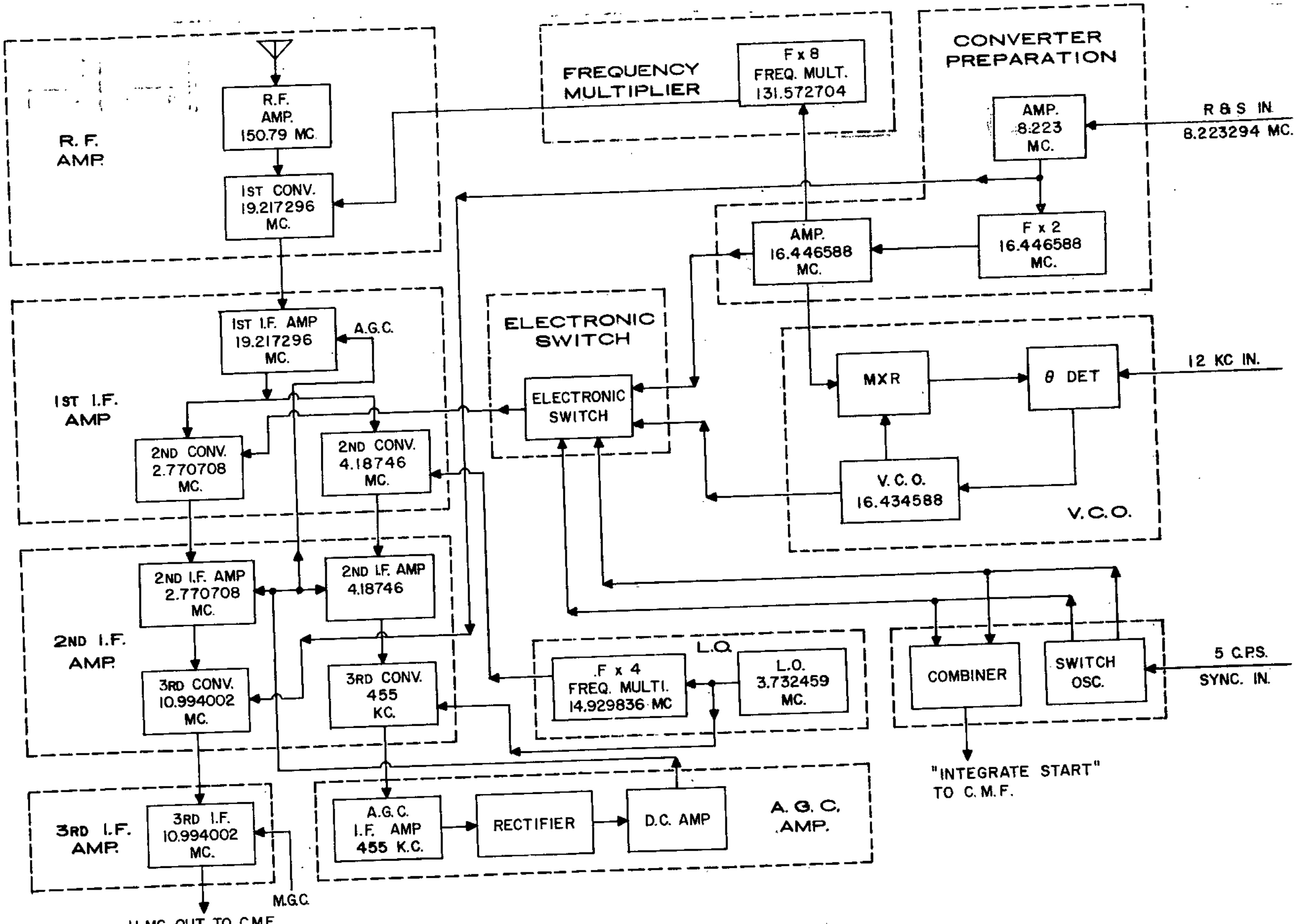


Figure 49 Schematic Block Diagram of Receiver

to be practical and to give a reduction of about one db in the noise figure of the receiver system. However, later attempts to use these amplifiers at the field stations gave unsatisfactory results. The high "Q" circuit seemed to be sensitive to temperature drift. This sensitivity combined with the narrow bandwidth seriously changed the overall performance. Since the improvement over vacuum tubes was only about one db and since the external noise was frequently higher than the receiver input noise, no further attempt was made to overcome the problems associated with the parametric amplifiers.

F. Study of Orbital Data Handling and Presentation

BRL Technical Note No. 1265, June 1959, entitled "Orbital Data Handling and Presentation" by R. E. A. Putnam, Report No. 3 ARPA Satellite Fence Series, discusses the problem associated with handling the data for the DOPLOC system. This is a preliminary study, the purpose of which is to present the relative merits and limitations of various alternates proposed; to indicate the particular methods worthy of serious consideration and further study; and to outline the time factors and development costs likely to be involved in procuring prototype equipment. Discussion is limited to a general, rather than to a specific treatment of the subject, because numerous pertinent details of instrumentation and orbital computational procedures were not stabilized at the time the report was written. The subtitles treated are "preliminary data editing, orbital data catalog, orbital comparisons, visual data displays". The following is a summary of conclusions reached.

a. Preliminary data editing by visual inspection of the Doppler "S" curve is believed to be essential, at least during the early stages of the project.

b. Orbital parameter data should be catalogued at the data analysis center in printed tabular form for operator reference, also in digital form for satellite identification and plotting board input. The choice of digital storage medium will be governed by facilities locally available, equipment complexity, commercial availability and cost factors.

c. A plotting board display appears to be justifiable for providing a visual check on satellite identification in doubtful cases.

d. Orbital charts produced on plotting board and distributed in advance to ground receiver stations may serve a useful purpose in alerting operators to the imminent approach of known satellites and their direction of approach.

e. It is recommended that prototype items of equipment hardware be assembled to demonstrate their suitability in handling actual orbital data before attempting to prepare final specifications for a field installation.

G. Synchronization of Tracking Antennas

BRL Technical Note No. 1278, September 1959, entitled "Synchronization of Tracking Antennas" by R. E. A. Putnam, Report No. 6, ARPA Satellite Fence Series, considers the problems associated with synchronizing scanning antennas.

Synchronizing a two-station complex to within $\pm$ 1 degree, relative to each other, requires that each individual station be synchronized to within $\pm$ 0.5 degree, relative to a common reference standard. In the table which follows are presented estimates of the relative component and total error magnitudes which might be expected from each of the three types of scanning antenna designs capable of meeting performance requirements.

		Estimated Error Magnitudes for Various Antenna Types		
Error Source		Rotatable	Element Switching	Controlled Phase Shift
1.	Station Timing	$\pm 0.03^\circ$	$\pm 0.03^\circ$	$\pm 0.03^\circ$
2.	Antenna Orientation	$\pm$ 0.02	$\pm$ 0.02	$\pm$ 0.02
3.	Antenna Pattern	$\pm$ 0.05	$\pm$ 0.05	$\pm$ 0.05
4.	Phasing	$\pm$ 0.05	$\pm$ 0.10	$\pm$ 0.35
5.	Structural Deformation	$\pm$ 0.15	$\pm$ 0.05	$\pm$ 0.05
6.	Scanning Beam Drive	$\pm$ 0.20	$\pm$ 0.10	$\pm$ 0.00
	Totals	$\pm 0.50^\circ$	$\pm 0.35^\circ$	$\pm 0.50^\circ$

It is to be noted that error ratings of the three antenna systems are identical for the first three error sources, and are believed to be reasonably representative of values that can be maintained under ordinary operating conditions. Incidentally, they add up to 20 per cent of the total error permissible. Inasmuch as error magnitudes from almost any source can be progressively reduced by concentrating on equipment and circuit refinement, it is reasonable to suppose that all three antenna types under discussion can be developed to the point where they meet the necessary performance requirements for this proposed project, if cost is not a factor. However comparative figures tabulated above strongly indicate that the switched element type of antenna has the distinct advantage of a lower error susceptibility, hence the probability that it will carry the lower price tag and a simplified maintenance program. Other conclusions reached are:

a. Sky-scanning antennas, synchronized to within ± 1 degree, appear to be technically feasible for station spacings up to, and somewhat in excess of 1000 miles.

b. Each station should include a precision time generator to permit continuing operation for a reasonable period following interruption of the external source of synchronizing signals.

c. Economic and other considerations indicate the desirability of synchronizing each station directly with WWV timing signals.

d. Sky-scanning rates influence station synchronization procedures and data transmission problems. It is desirable that a scanning rate be selected such that the resulting number of scan cycles per minute becomes a whole number.

e. It is not essential that the angular scan rate be completely uniform throughout the sweep range, but it is important that any non-linearities be identical for both stations of a pair.

f. Sky-scanning arrangements with a reciprocating sweep may be subject to non-linear components of motion in one direction that are not duplicated in the reverse direction, thus complicating synchronization procedures. For this reason, beams that sweep continuously in one direction are to be preferred.

g. A fixed antenna structure, where in a scanning beam is generated by progressive switching of radiating elements, appears to be the most practical antenna type.

h. Some moderate decrease in beam width, or some increase in beam scanning rate, appear to be feasible, if desired. However, such changes tend to impose increasingly severe requirements on the synchronization problem, and at some point a limit will be reached beyond which further changes will be impractical. Whether synchronization requirements can be met with beamwidths of only one degree is problematical.

H. Precision Frequency Measurement of Noisy Doppler Signals

BRL Report No. 1110, June 1960, entitled "Precision Frequency Measurement of Noisy Doppler Signals", by William A. Dean, Report No. 15 in the BRL DOPLOC Satellite Fence Series, gives the results of a brief study of the uncertainty expected in measuring the frequency of a radio Doppler signal from the data gathering equipment of the DOPLOC satellite tracking station. Two methods of measurement are alternately used depending upon the cycle count and the desired precision. One method simply counts Doppler cycles from the tracking filter for a given time period, for example, one second. The second method is indirect and integrates a chosen number of Doppler cycles over which period a high frequency, say 10 mc standard frequency is counted. Since the resolution of the counter is $\pm$ 1 cycle, yielding a counting precision of $\pm\sqrt{2}$ cycles per second when both ends of the interval are concerned, the precision of the 10 mc count is considerable improved over that of a Doppler count of from zero to a few thousand cycles/second.

The random scatter varies with propagation phenomena and the angle of elevation of the satellite with respect to the observation station, but may be as much as 3 cycles per second. This scatter is of such character

that it does not affect the operation of the tracking filter. Typical conditions are plotted in the report where at an input frequency of 10 kc an input signal to noise ratio of -18db, and a tracking filter bandwidth of 10 cps, peak excursions of 0.16 cps were observed and the rms frequency error was 0.652 cps.

I. Contract DA-04-200-ORD-674, Stanford Research Institute, System Studies

Under contract DA-04-200-ORD-674, Stanford Research Institute conducted a DOPLOC system study which lead to two reports. The first of these is entitled Final Report, Part A, Station Geometry Studies for the DOPLOC System by W. E. Scharfman, H. Rothman and T. Morita. This report is number 9 in the BRL DOPLOC satellite fence series. It pertains entirely to the interim type system which utilizes fixed antenna beams oriented in such a manner as to obtain data for segments of an "S" curve. An analysis was made of the relation between the layout of the receiving and transmitting stations of the BRL CW reflection Doppler system (for the detection of non-radiating satellites) and such factors as antenna gain, pattern shapes, time of transit of a beam by a satellite and coverage for fixed-beam antennas.

The results of the study show the regions in space where sufficient data would be obtained to determine the satellite's orbital parameters, and the complexity of the required antenna system for various station geometries and satellite altitudes. This report is classified confidential and is therefore not abstracted in detail here.

The second SRI report is entitled "Final Report, Part B, DOPLOC System Studies" by W. E. Sharfman, H. Rothman, H. Guthart and T. Morita and is Report No. 10 in the BRL DOPLOC Satellite Fence Series.

Part B of this final report shows that because of the variation in refractive index of the ionosphere, an error is introduced in the determination of the radial velocity of a moving target. This error results because the direction of the refracted ray at the target differs from the line-of-sight direction. The Doppler error introduced arises from conditions at the actual instantaneous position of the satellite rather than from the integrated effort of conditions along the entire propagation path. This error

is greatest when the satellite is at the level where the ionization is most dense, at the maximum of the F2 layer (300 KM). Here the error amounts to about 0.25 per cent of the Doppler frequency for a carrier frequency of 100 mc.

The Faraday effect causes a rotation of the plane of polarization of a radio wave passing through an ionized medium in the presence of a magnetic field. As a typical example the number of rotations that a 100 mc wave might incur in a double passage through an ionosphere 260 KM thick, at a height of 150 KM, varies from about 20 at zero degrees elevation to about 5 at 90 degrees elevation.

This report shows that the Luxembourg effect, or ionospheric cross-modulation effect, can be neglected for frequencies above 4 mc. Hence cross-modulation at 100 mc should be extremely small. It is also shown that the atmospheric noise generated in the troposphere is at least 40 db less than cosmic noise at 100 mc and can therefore be neglected.

Forward-scatter propagation involves scattering either by ionospheric or tropospheric inhomogeneities in the common volume of the transmitting and receiving antenna beams. For frequencies above 100 mc and separation less than 600 miles, the tropospheric transmission component appears to dominate. Typical features of the tropospheric scatter are that it decreases rapidly with increasing distance, and decreases very slowly with increasing frequency. For a station separation of 450 miles, the average signal level with optimum antenna orientation will be about 90 db below that expected at the same distance in free space with the same power and same antennas. Free-space attenuation at this frequency and separation is 130 db. This received signal level is considerably greater than the received signal expected from forward scattering of the satellite. The actual tropospheric signal received is further below the free space signal since the side lobes and not the main beams will be forming the common volume.

SRI specifically investigated the question, as to whether the noise figure could be reduced by reducing the temperature of the antenna or of any reasonable volume surrounding the antenna. At 100 mc the background noise temperature is about 800 degrees K, while some areas of the sky (notably the galactic center) have temperatures up to thousands of degrees Kelvin. It is shown that if a receiver has a 3-db noise figure and an apparent antenna temperature of 800 degrees K, the operating noise figure will be 5.5 db. It is therefore concluded that no reduction in noise figure would be achieved by cooling either the antenna or the volume immediately surrounding it.

The effects of meteors and meteor trails have been discussed briefly elsewhere in this report. SRI presents an extensive analysis of the effects to be expected from both meteors and meteor trails. This treatment is too extensive to abstract here except for the following remarks. The specular echo count for meteor trails with initial line densities of 10^{14} electrons per meter is directly proportional to the square root of the transmitter output power and the receiver sensitivity. The interim DOPLOC system was sensitive to trails with line densities of the order of 10^{12} electrons per meter. If the system were to become sensitive to line densities of less than 10^{10} electrons per meter, the count might become directly proportional to these system factors, and possibly even proportional to their square or cube. Various methods such as increasing the frequency, the incorporation of filters, etc. are available to discriminate against meteor trail signals.

The remainder of Part B of the SRI report treats the effects of antenna phase patterns and suggests antenna systems for the DOPLOC system. For this treatment the reader is referred to the basic report.

J. Comb Filter Development

Since the lead time for the development of the circulating memory filter was known to be at least 12 months and the cost approximately $250,000, it was decided to look for a second method of obtaining narrow band filter action on the data from the scanning antenna DOPLOC system. The search and lock-on time for the phase locked tracking filters was too

long to permit these filters to operate with scanning antennas. Therefore a program was initiated to develop simultaneously with the circulating memory filter a comb type filter.

Starting with a 10-cycle filter pass band and a possible 12-kc band of Doppler frequencies to be covered, it is at once apparent that 1200 individual filters would be required to cover the entire band. It was therefore decided to build only a section of the filter for test purposes. The result was one hundred and eighty individual ten cycle filters spaced 20 cps apart to cover a total of 3600-cps bandwidth. This input was to be switched three times to cover the 12-kc band. The rate of change of Doppler frequency varies with altitude of the satellite from approximately 25 to 100 cps. This maximum rate of 100 cps determines the minimum usable bandwidth of 10 cps. This in turn sets the maximum time available to recognize the Doppler signal as 100 milliseconds. This maximum time determines the maximum scan rate for a given antenna beamwidth. Since twelve data points are desired to insure sufficient data for a convergent solution from a single pass, there is also a minimum scan rate associated with the low altitude passes for a scan rate that would give 12 data points on a pass and an integration time of 100 m.s., a beamwidth of approximately 1 degree is indicated.

Describing the filter action briefly, the output of the receiver is fed through a noise actuated automatic gain control circuit, thence to the filter comb, each filter of which has an amplifier, AGC, and threshold control circuit which feeds a multi-pen recorder. A record indicates a signal of frequency corresponding to the filter frequency present at the input to the comb. This comb filter has been completed and tested on both real time and simulated tracking data and found to perform satisfactorily. It is described in full detail in BRL Memorandum Report No. 1349 entitled "A Comb Filter for Use in Tracking Satellites", by R. Vitek.

Figures 50 to 57 inclusive are photographs of actual recordings made at the output of the comb filter. Figures 50 to 54 show the performance characteristics of the filter with simulated data. Figures 55 to 57 are

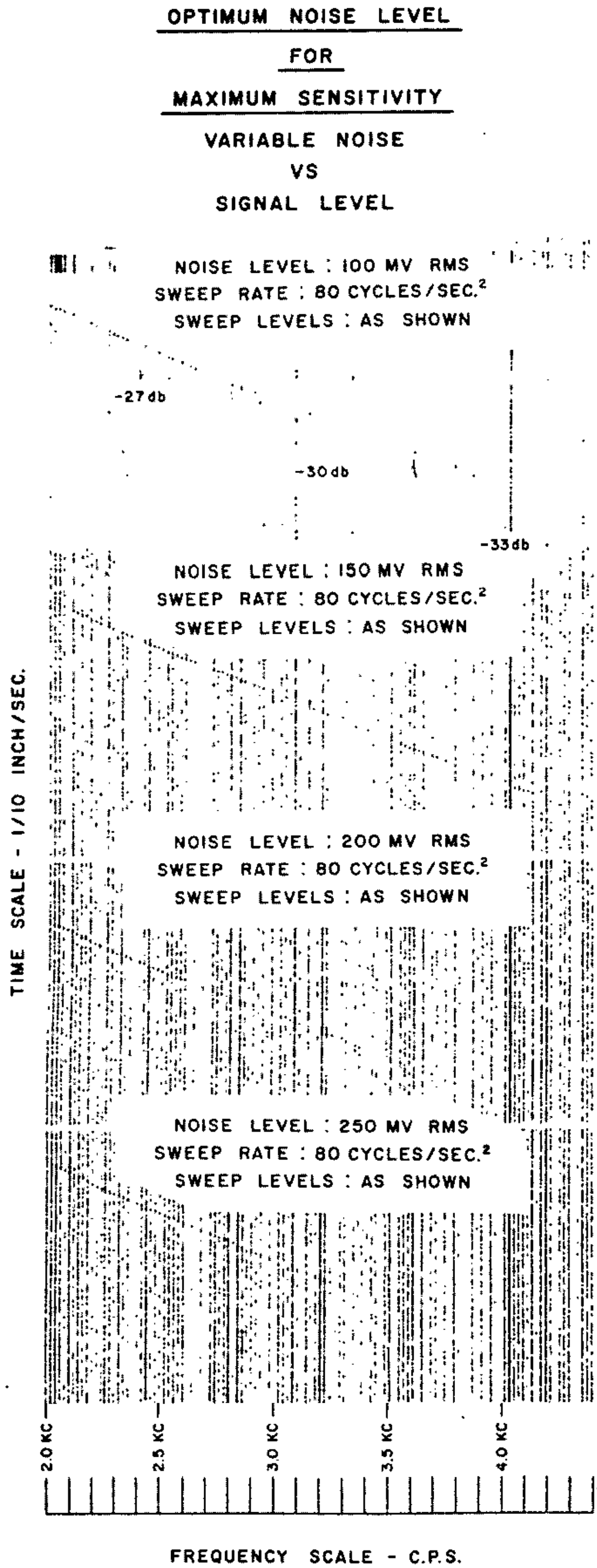


Figure 50 Optimum Noise Level for Maximum Sensitivity (Variable Noise vs Signal Level)

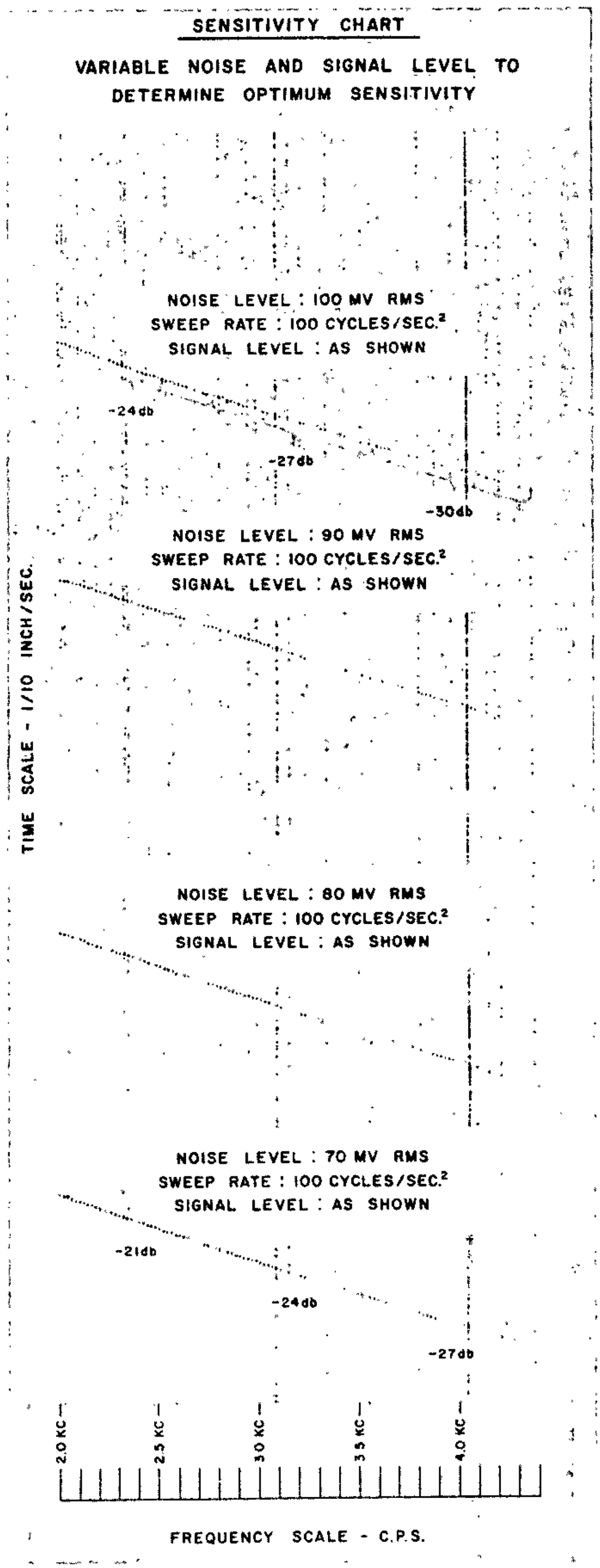


Figure 51 Sensitivity Chart

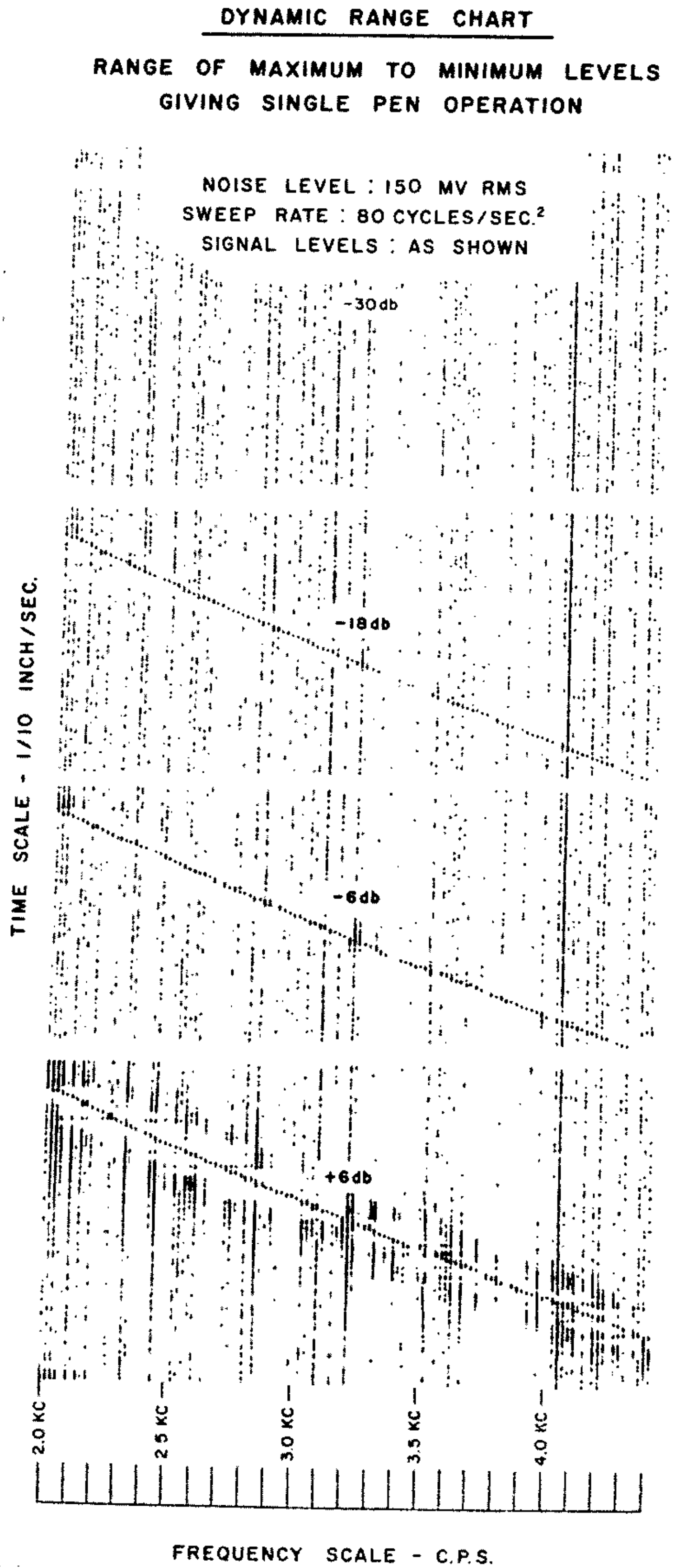


Figure 52 Dynamic Range Chart

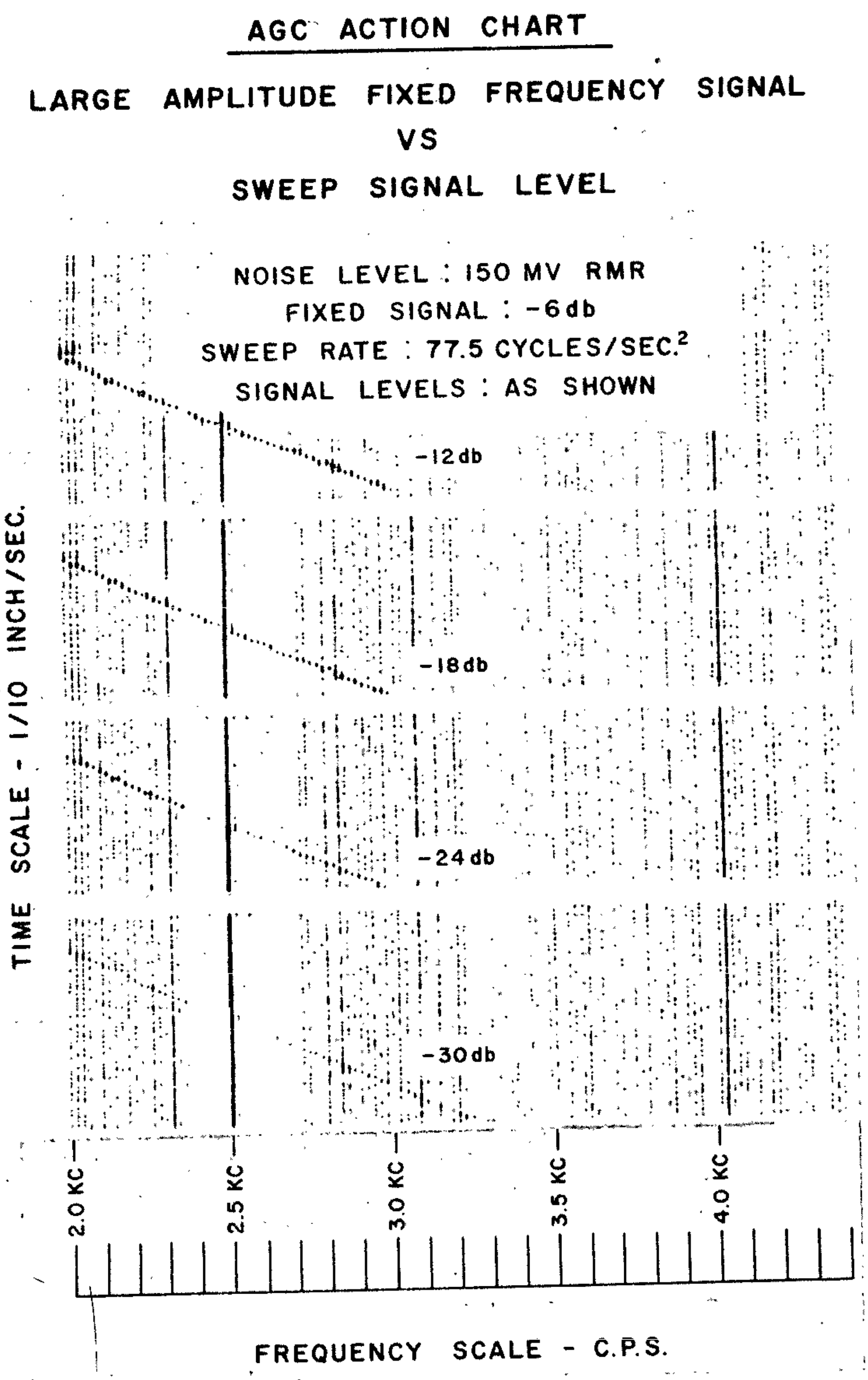


Figure 53 AGC Action Chart

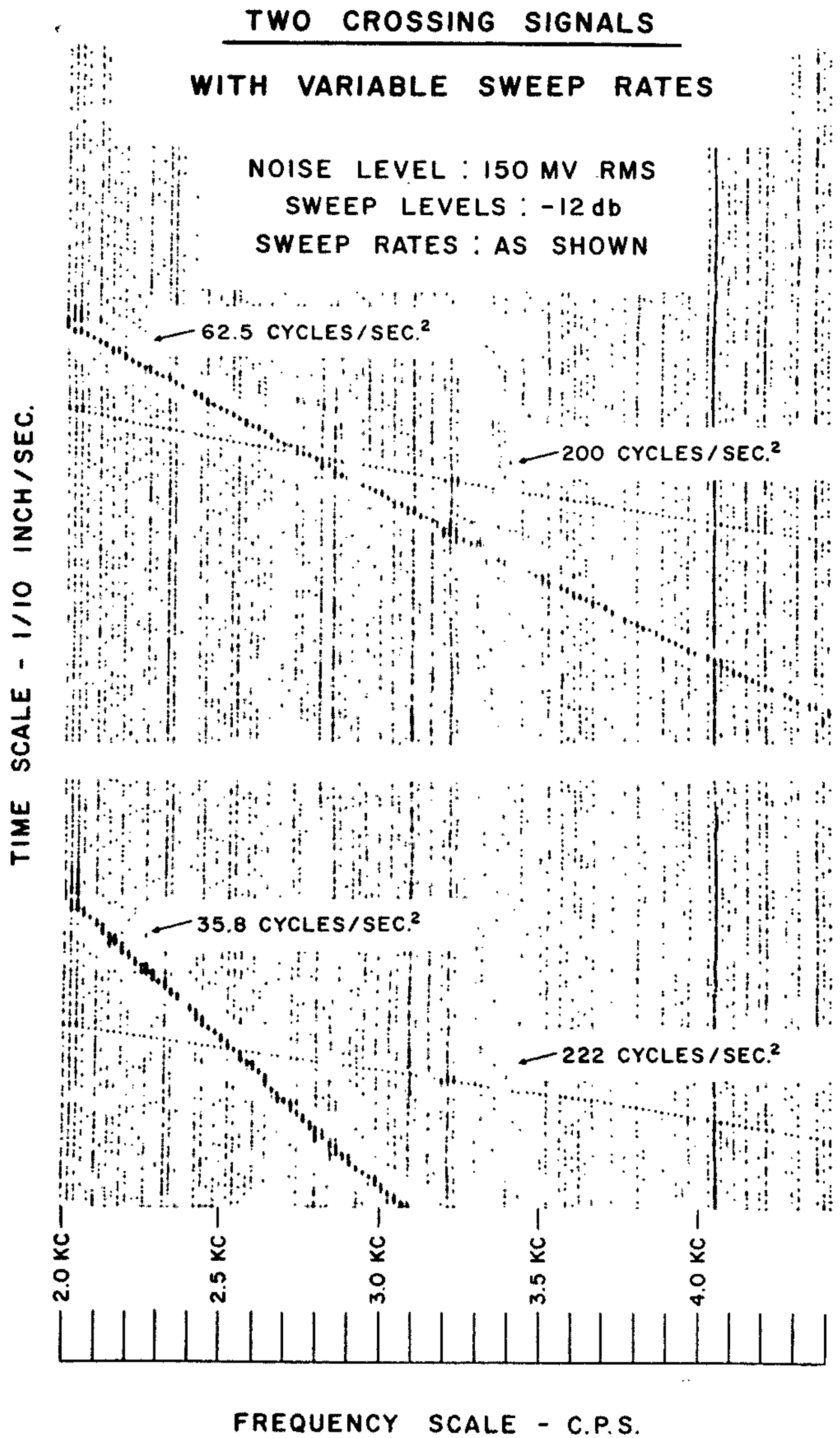


Figure 54 Two Crossing Signals with Variable Sweep Rates

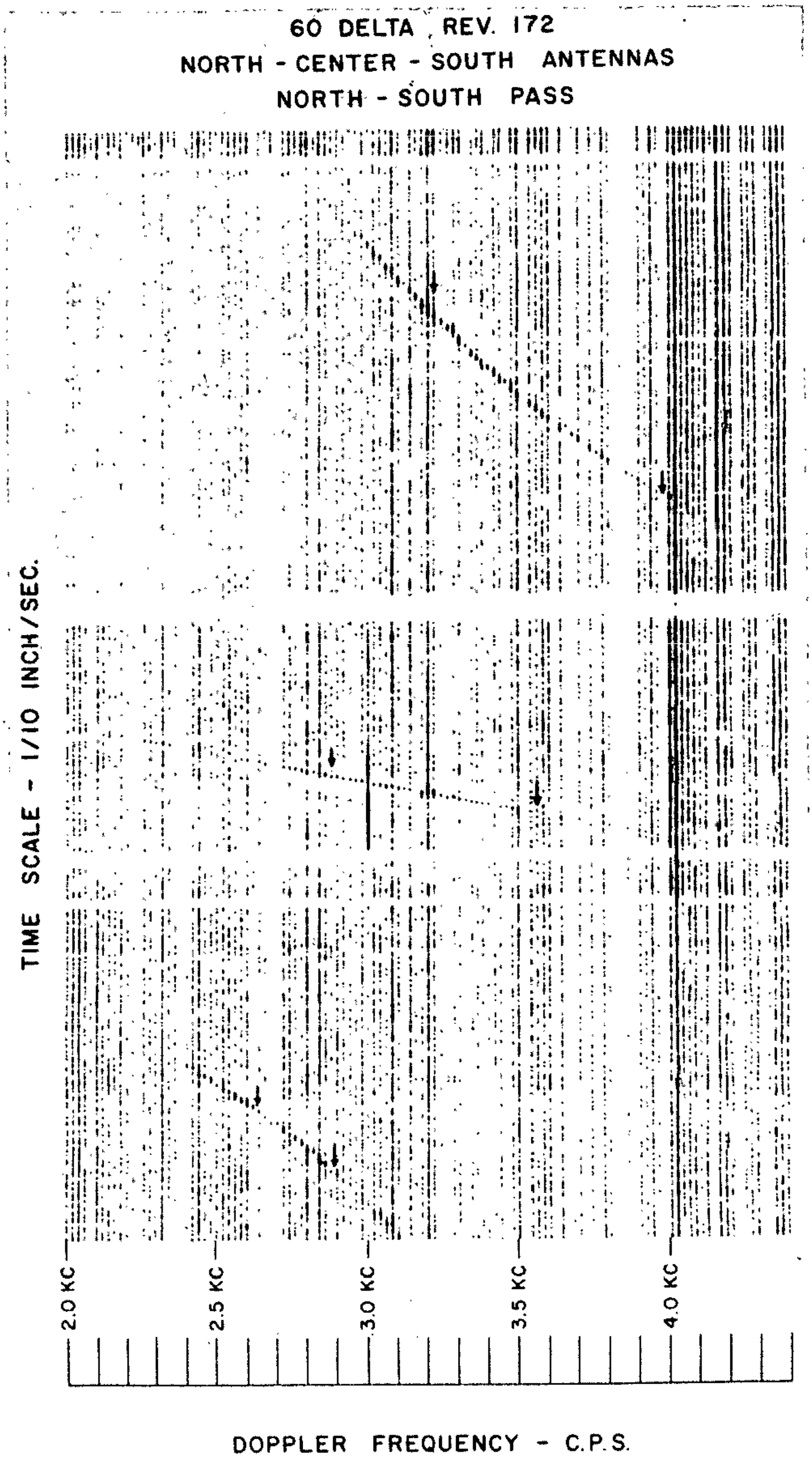


Figure 55 60 Delta Rev. 172

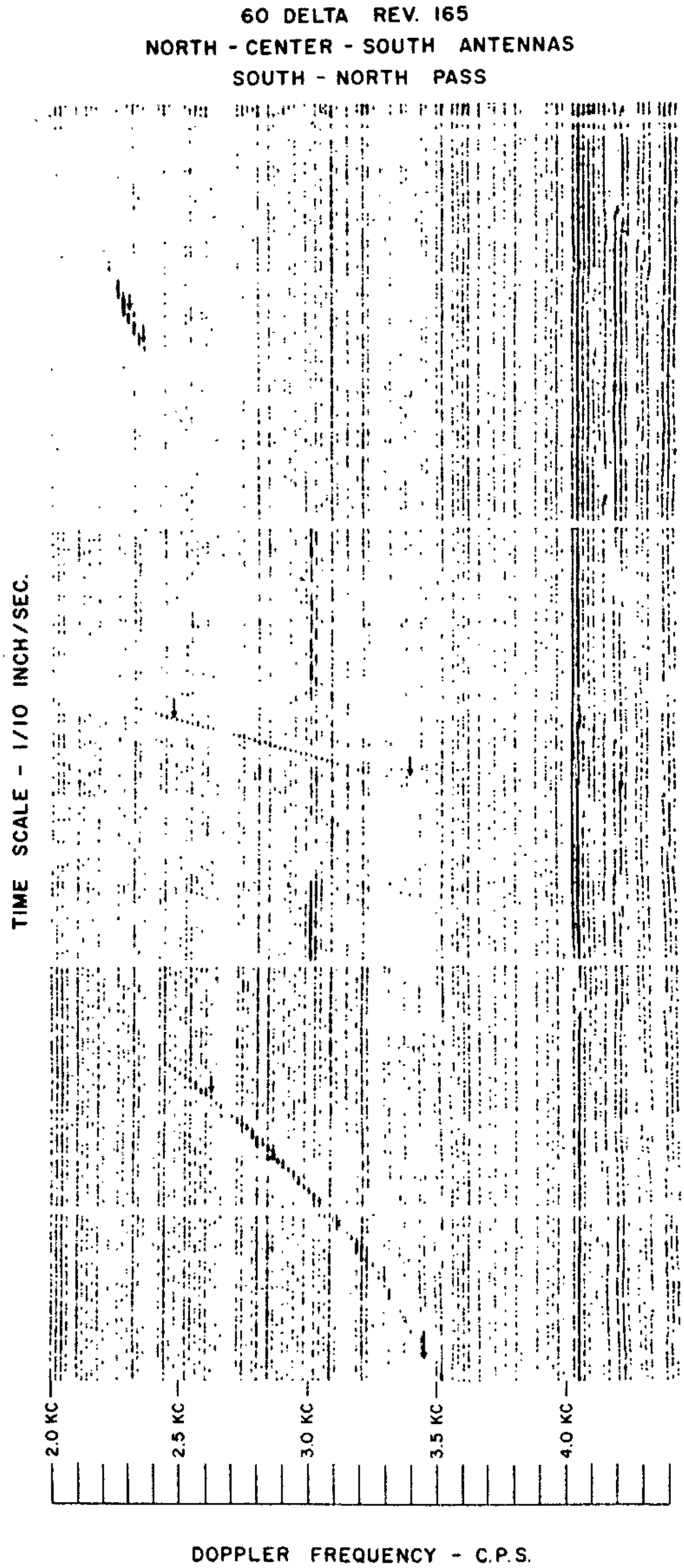


Figure 56 Delta Rev. 165

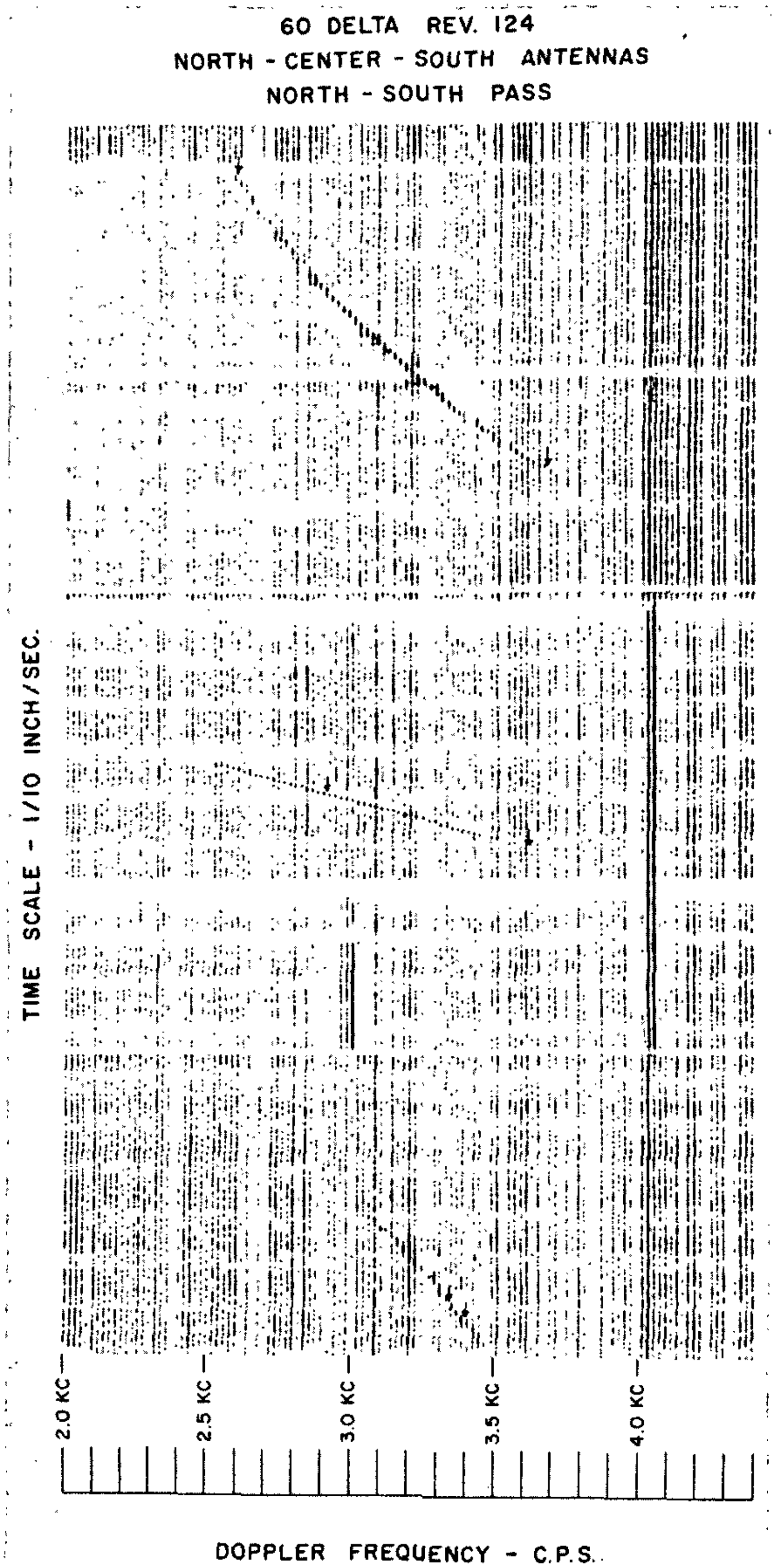


Figure 57 60 Delta Rev. 124

copies of satellite pass data from magnetic tapes recorded on the interim DOPLOC system at Forrest City, Arkansas. Chart records are also available of the performance of the ALO - tracking filter equipment on these passes. The arrows on the records indicate the frequency limits of the tracking filter records. In general the comb filter tracked the signal for a longer period than did the tracking filter. This was expected since the best sensitivity of the ALO was 21 db. It could not therefore pick up the signal as soon as the comb filter. After a lock was obtained the tracking filter was independent of the ALO and its sensitivity was identical to that of the comb filter. The test records of simulated and actual satellite signals are indicative of a high level of performance. The comb filter prototype met all of the design requirements. The unit is fully capable of being expanded to the full complement of 1200 filters and of providing an effective tracking capability for the proposed DOPLOC scanning system. It could provide an excellent means of tracking any short duration signals having a high rate of frequency change. The frequency accuracy is limited to $\pm$ 2 cps with the 10-cps bandwidth filter elements.

VII. SATELLITE ORBIT DETERMINATION FROM DOPLOC DATA

R. B. Patton, Jr.

A. Introduction

Computing methods have been developed which provide the DOPLOC system with the capability of detecting and identifying non-radiating satellites. While these methods have been derived specifically for Doppler-type tracking systems, the computing procedures are sufficiently flexible that, with minor modification, they may be applied to observations from any satellite or ICBM tracking system. Moreover, they provide relatively accurate orbital determinations when the tracking observations are limited to a few minutes of data recorded at a single receiver in the course of a single pass of a satellite. This capability is fundamental for a detection system. In addition, the computing program has been extended to provide a highly accurate solution when the input data are increased to include observations from more than a single pass of the satellite or from more than one receiver.

A prime requirement for a satellite detection system is the capability of establishing an orbit within minutes after the first pass over the tracking system. The computing program presented here provides the DOPLOC system with the capacity for orbit determination within one to five minutes after satellite passage. Further, these methods function effectively with as few as 6 to 12 observations recorded at a single receiver over a 2 to 3 minute interval. It is doubtful whether any other satellite detection system can provide equivalent accuracy for first pass detection. Moreover, many have no capability whatever for orbital determination from single-pass observations.

Computing programs for multiple-pass solutions have been under consideration for sometime. Although the development of these methods has not been completed, a relatively simple procedure is emerging which provides sufficient accuracy for positive identification. In addition, these results may be used to predict position with enough precision to be used as an aid in future acquisition. Although this work is not complete, the method

appears to be both practical and useful. Moreover, the initial results from solutions with actual field data are very promising and have, therefore, been included in the section, "Computational Results".

In practice, orbital determination from DOPLOC observations is accomplished in three phases:

1. Initial approximations for position and velocity are established from frequency and slope measurements near the inflection point of the Doppler frequency time curve for each set of observations.

2. These results are used as input to obtain single-pass solutions for individual sets of observations. Such computations yield moderately accurate Keplerian orbital parameters to be used for initial identification.

3. The single-pass results are used to initiate a multiple-pass solution which simultaneously combines observations from several passes to compute a perturbed orbit with sufficient accuracy to provide both positive identification and practical prediction.

The first two steps in the computing procedure have been completely developed and thoroughly tested with numerous sets of actual field data. Development of the multiple-pass solution is nearing completion. Limited, but successful, testing has been accomplished with field observations.

B. Description of Observed Data

Doppler observations consist of recordings of Doppler frequency as a function of time. Here the Doppler frequency is defined as the frequency obtained by heterodyning a locally generated signal against the signal received from the satellite followed by a correction for the frequency bias introduced as a result of the difference between the frequency of the local oscillator and that of the signal source. The Doppler frequency is defined to be negative when the satellite is approaching the receiving site and positive when it is receding. If the Doppler frequency, as defined, is plotted as a function of time, one obtains curves of the form shown in Figure 58, usually referred to as "S" curves. The asymmetry of the curves is typical for a tracking system with a ground-based transmitter and a

receiver separated by an appreciable distance. Only for a satellite, whose orbital plane either bisects or is orthogonal to the base line, will the Doppler data produce a symmetrical "S" curve with a reflection system. With a satellite-borne transmitter, the "S" curve is very nearly symmetrical, being modified slightly by the earth's rotation and the refractive effect of the ionosphere. If continuous observations are made and sampled at frequent intervals, such as once per second, Figure 58 (a) illustrates an analog plot of the data available for computer input. However, with a ground-based transmitter it is necessary to limit the number of observations in order to minimize equipment cost and complexity. For example, the three beam antenna complex of the interim DOPLOC system provides three sections of the "S" curve as shown in Figure 58 (b). Another possibility is the use of a scanning antenna beam to provide discreet observations at regular intervals as shown in Figure 58 (c). Such data could be obtained by an antenna with a thin, fan-shaped beam which scanned the sky repetitively.

Any of these sets of data may be used readily as input for the computing procedures. Whenever possible, this input consists of the total cycle count rather than the Doppler frequency, i.e., the area under the curves or arcs of curves presented in Figure 58 (a) and (b). Hence, this method of solution is based, in a sense, upon every available observation rather than upon a selected few of the total observations (which would be the case if the computing input were limited to a representative number of frequency measurements). Experience has shown this to yield a very significant gain with regard to the accuracy and convergent properties of the solution.

C. The Single-Pass Solution

The method of solution consists of a curve-fitting procedure in which a compatible set of approximations for the orbital parameters, are improved by successive differential corrections. The latter are obtained from a least-squares treatment of an over-determined system of equations of condition. The imposed limitation of single-pass detection permits several assumptions which considerably simplify the computing procedure. Among these

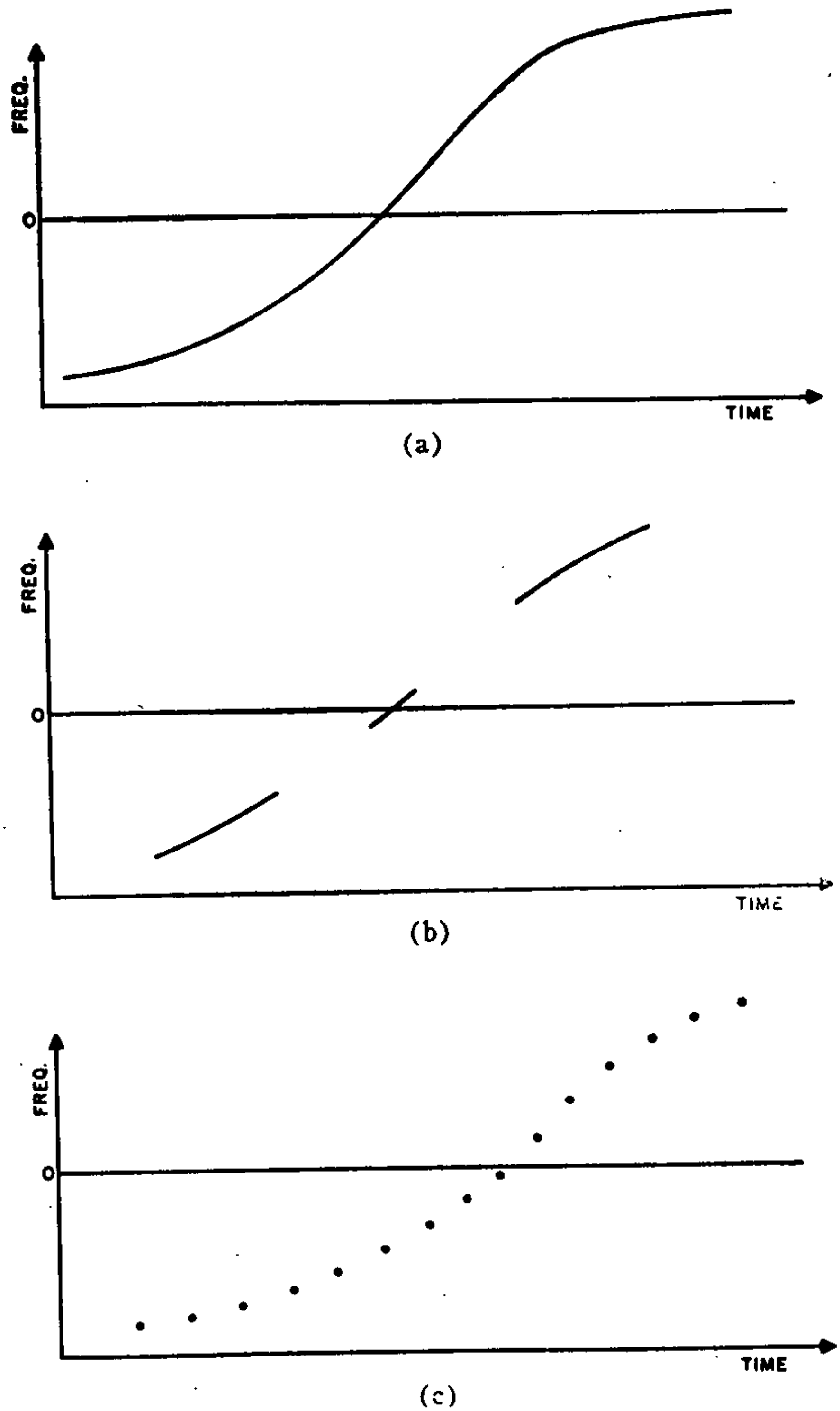


Figure 58 (a) (b) (c) —Doppler frequency-time curves.

is the assumption that the Earth may be treated dynamically as a sphere while geometrically regarding it as an ellipsoid. In addition, it is assumed that no serious loss in accuracy will result if drag is neglected as a dynamic force. With these assumptions, it is apparent that the satellite may be regarded as moving in a Keplerian orbit. An additional simplification in the reduction of the tracking data is warranted if the frequency of the system exceeds 100 megacycles; for it then becomes feasible to neglect both the atmospheric and ionospheric refraction of the transmitted signal.

In formulating the problem mathematically, it is helpful to regard the instrumentation as an interferometer. In this sense, the total number of Doppler cycles observed within any time interval will provide a measure of the change in the sum of the slant ranges from the satellite to the transmitting and receiving sites. If λ is the wavelength of the radiated signal and N_{ij} the total number of Doppler cycles resulting at the ith receiver from the motion of the satellite between times t_j and t_{j+1}, it follows that $v_{ij} \equiv \lambda N_{ij}$ is a measure of the total change in path length from the transmitter to the satellite to the ith receiver between times t_j and t_{j+1}. Let g_{ij} be defined as the actual change in path length. It follows from Figure 58 that:

$$g_{ij} = (TS_{j+1} + R_iS_{j+1}) - (TS_j + R_iS_j), \tag{1}$$

where T is the transmitting site, R_i the location of the ith receiver, S_{j+1} the position of the satellite at time t_{j+1}, and S_j the position of the satellite at time t_j. In the event that the observations consist only of discrete measurements of frequency, the same definitions will apply, but the time interval from t_j to t_{j+1} will be limited to one second.

The solution consists of improving a set of position and velocity components which have been approximated for a specific time. The latter will be defined as t_o, and as a matter of convenience, it is generally taken as a time near the inflection point of the "S" curve. Although the location of the coordinate system in which the position and velocity vectors are

defined is relatively immaterial from the standpoint of convergence, a system fixed with respect to the Earth's surface does provide two distinct advantages. First, the function g_{ij} is somewhat simplified since the coordinates of the instrumentation sites remain fixed with respect to time. Of greater significance, however, is the fact that the method may be altered to accept other types of measurements for input by merely changing the definition of the function g_{ij} and correspondingly, the expressions for its derivatives, with no additional modification to the balance of the procedure which in fact, constitutes the major portion of the computing process.

The set of initial approximations for the position and velocity components are defined for time t_o as $(x_o, y_o, z_o, \dot{x}_o, \dot{y}_o, \dot{z}_o)$. The reference frame is the xyz-coordinate system which is defined in the following section. If second and higher order terms are omitted from the Taylor expansion about the point $(x_o, y_o, z_o, \dot{x}_o, \dot{y}_o, \dot{z}_o)$, the equations of condition may be written in matrix form,

$$\Delta V = J \Delta X, \tag{2}$$

where

$$J \equiv \left(\frac{\partial g_{ij}}{\partial x_o}, \frac{\partial g_{ij}}{\partial y_o}, \frac{\partial g_{ij}}{\partial z_o}, \frac{\partial g_{ij}}{\partial \dot{x}_o}, \frac{\partial g_{ij}}{\partial \dot{y}_o}, \frac{\partial g_{ij}}{\partial \dot{z}_o} \right),$$

$$\Delta V \equiv (\Delta v_{ij}) = (v_{ij} - g_{ij}), \tag{3}$$

$$\Delta X \equiv \begin{pmatrix} \Delta x_o \\ \Delta y_o \\ \Delta z_o \\ \Delta \dot{x}_o \\ \Delta \dot{y}_o \\ \Delta \dot{z}_o \end{pmatrix},$$

for all values of i and j. Hence, J is a matrix of order $(i \cdot j \times 6)$, ΔV a

matrix of order ($i \cdot j$x1), and ΔX a matrix of order (6x1). Since there are six unknowns, a minimum of six equations are required for a solution. In practice, sufficient data are available to provide an over-determined system, thus permitting the least squares solution,

$$\Delta X = (J^* J)^{-1} J^* \Delta V, \tag{4}$$

where J^* is the transpose of the Jacobian J. Finally, improved values for the initial conditions are obtained from

$$X + \Delta X,$$

where

$$X = \begin{pmatrix} x_o \\ y_o \\ z_o \\ \dot{x}_o \\ \dot{y}_o \\ \dot{z}_o \end{pmatrix} .$$

As a matter of convenience, no subscripts were introduced to indicate iteration; but at this point, the improved values of X are used for the initial point and the process is iterated until convergence is achieved.

Since the function g_{ij} cannot be expressed readily in terms of X directly, the evaluation is obtained implicitly. An ephermeris is computed for the assumed values of the position and velocity vectors at time t_o. Then using equation (1), g_{ij} may be evaluated for all values of i and j.

In the process of this evaluation, it is expedient to use two rectangular coordinate systems in addition to the Earth-bound system whose origin is at the transmitting site. Referring to Figure 60 these coordinate systems are defined as follows.

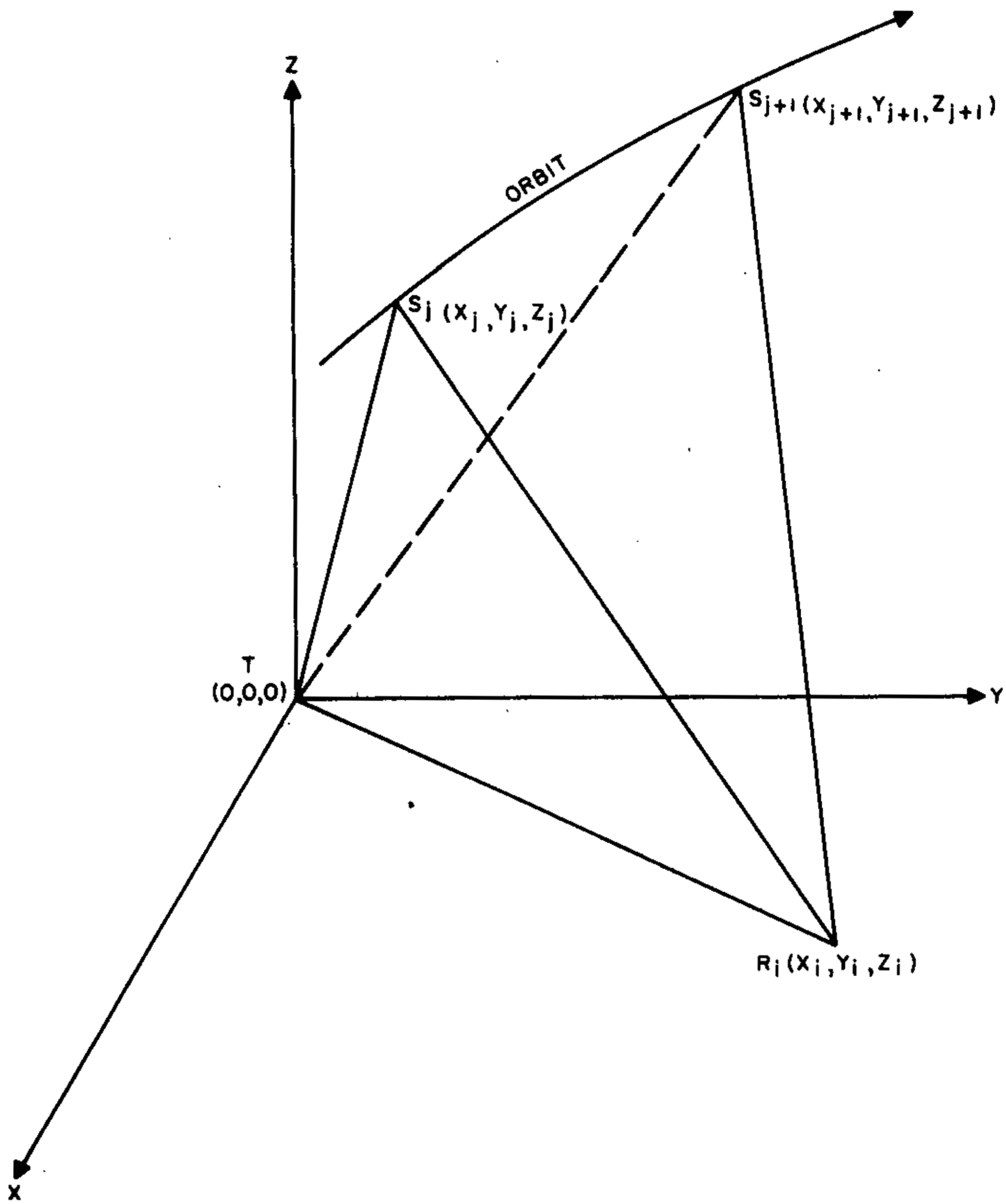


Figure 59 - Problem geometry.

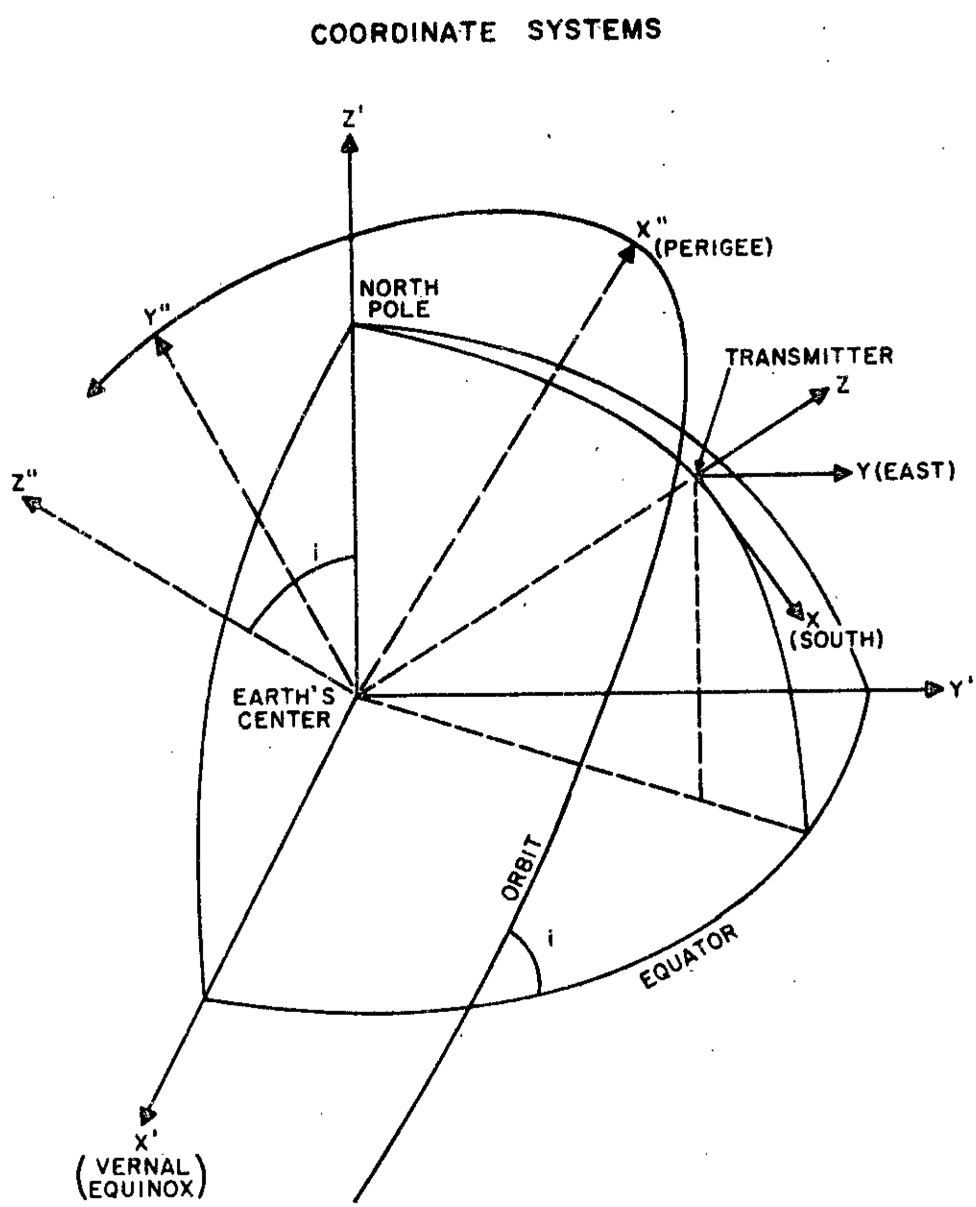


Figure 60 - Coordinate systems.

1. The xyz-coordinate system is a right-hand rectangular system with the origin on the Earth's surface at the transmitter. The x axis is positive south, the y axis is positive east and the z axis is normal to the Earth's surface at the transmitting site.

2. The x'y'z'-coordinate system is a right-hand rectangular system with the origin at the Earth's center. The x' axis lies in the plane of the equator and is positive in the direction of the vernal equinox, while the positive z' axis passes through the north pole. The y' axis is chosen so as to complete a right-hand system.

3. The x"y"z"-coordinate system is likewise a right-hand rectangular system with the origin at the Earth's center. The x"y" plane lies in the orbital plane of the satellite, with the positive x" axis in the direction of perigee. The positive z" axis forms with the positive z' axis an angle equal to the inclination of the orbital plane to the plane of the equator. The y" axis is chosen so as to complete a right-hand system.

The first step in this phase of the computation consists of computing values for the initial position and velocity components in the x'y'z'-coordinate system. This may be achieved by one rotation and one translation which are independent of time, and a second rotation which varies with time. Let the notation $R_i(\alpha)$ indicate the matrix performing a rotation through an angle α about the ith axis of the frame of reference such that the angle is positive when the rotation is in the right-hand direction and i is equal to 1, 2 or 3, according to whether the rotation is about the x, y or z axis respectively. The desired transformation follows,

$$\begin{bmatrix} x_o' \\ y_o' \\ z_o' \end{bmatrix} = R_3(-\Theta_o)R_2(\phi - 90^\circ) \left(\begin{bmatrix} x_o \\ y_o \\ z_o \end{bmatrix} + \begin{bmatrix} \rho_\phi \sin \Delta \\ 0 \\ \rho_\phi \cos \Delta \end{bmatrix} \right) , \tag{5}$$

$$
\begin{pmatrix} \dot{x}'_o \\ \dot{y}'_o \\ \dot{z}'_o \end{pmatrix} = \dot{R}_3(-\Theta_o)R_2(\phi - 90^o)
\left[\begin{pmatrix} x_o \\ y_o \\ z_o \end{pmatrix} + \begin{pmatrix} \rho_\phi \sin \Delta \\ 0 \\ \rho_\phi \cos \Delta \end{pmatrix} \right]
+ R_3(-\Theta_o)R_2(\phi - 90^o) \begin{pmatrix} \dot{x}_o \\ \dot{y}_o \\ \dot{z}_o \end{pmatrix}, \qquad (6)
$$

where

$\dot{R}_3(-\Theta_o) \equiv$ the time derivative of $R_3(-\Theta_j)$ when $\Theta_j = \Theta_o$,

$\Theta_j \equiv$ the right ascension of the transmitting site at time t_j,

$\phi \equiv$ the geodetic latitude of the transmitting site,

$\rho_\phi \equiv$ the radius vector from the Earth's center to a point on the Earth's sea level surface at the latitude ϕ,

$\Delta =$ the difference between the geodetic and geocentric latitudes at the transmitting site.

The next step in the computation involves the evaluation of the following orbital parameters:

$a \equiv$ semi-major axis,

$e \equiv$ eccentricity,

$\sigma \equiv$ mean anomaly at epoch,

$i \equiv$ inclination,

$\Omega \equiv$ right ascension of the ascending node,

$\omega \equiv$ argument of perigee.

The evaluation of these orbital parameters is obtained from the following equations*:

* Derived by Dr. B. Garfinkel, Ballistic Research Laboratories, Aberdeen Proving Ground.

$$r_o = \sqrt{(x_o')^2 + (y_o')^2 + (z_o')^2} \quad , \tag{7}$$

$$v_o = \sqrt{(\dot{x}_o')^2 + (\dot{y}_o')^2 + (\dot{z}_o')^2} \quad , \tag{8}$$

$$r_o\dot{r}_o = \dot{x}_o'x_o' + y_o'\dot{y}_o' + z_o'\dot{z}_o' \quad , \tag{9}$$

$$\mu = gR^2 \ ,$$

where g is the mean gravitational constant and R is the radius of the Earth, which is assumed to be spherical in the development of the equations,

$$a = \frac{\mu r_o}{2\mu - r_o v_o^2} \tag{10}$$

$$e = \left| \frac{(r_o\dot{r}_o)^2}{\mu a} + \left(1 - \frac{r_o}{a}\right)^2 \right|^{1/2} , \tag{11}$$

$$E_o = \tan^{-1}\left\{\frac{r_o\dot{r}_o}{\sqrt{\mu a}\left(1 - \frac{r_o}{a}\right)}\right\} + \frac{\pi}{2}\left\{1 - \operatorname{sgn}\left(1 - \frac{r_o}{a}\right)\right\} , \tag{12}$$

where

$$\operatorname{sgn}\left(1 - \frac{r_o}{a}\right) = 1 \quad \text{if} \quad \left(1 - \frac{r_o}{a}\right) > 0 \ ,$$

$$\operatorname{sgn}\left(1 - \frac{r_o}{a}\right) = -1 \quad \text{if} \quad \left(1 - \frac{r_o}{a}\right) < 0 \ ,$$

$$n = \sqrt{\frac{\mu}{a^3}} \ , \tag{13}$$

$$\sigma = E_o - e \sin E_o - nt_o \ , \tag{14}$$

$$h_1 = y_o'\dot{z}_o' - z_o'\dot{y}_o' \ , \tag{15}$$

$$h_2 = z_o'\dot{x}_o' - x_o'\dot{z}_o' \ , \tag{16}$$

$$h_3 = x_o'\dot{y}_o' - y_o'\dot{x}_o' , \tag{17}$$

$$h = \sqrt{h_1^{\,2} + h_2^{\,2} + h_3^{\,2}} , \tag{18}$$

$$k_1 = \frac{h_1}{h} , \tag{19}$$

$$k_2 = \frac{h_2}{h} , \tag{20}$$

$$k_3 = \frac{h_3}{h} , \tag{21}$$

$$T = \sqrt{h_1^{\,2} + h_2^{\,2}} , \tag{22}$$

$$N_1 = - \frac{h_2}{T} , \tag{23}$$

$$N_2 = \frac{h_1}{T} , \tag{24}$$

$$i = \cos^{-1} k_3 \text{ , where } 0 \lesssim i \lesssim \pi , \tag{25}$$

$$\bar{x} = a(\cos E_o - e), \tag{26}$$

$$\bar{y} = a(\sin E_o)\sqrt{1 - e^2} , \tag{27}$$

$$r_o \cdot N = x_o'N_1 + y_o'N_2 , \tag{28}$$

$$r_o \times k \cdot N = N_1(y_o'k_3 - z_o'k_2) + N_2(z_o'k_1 - x_o'k_3) , \tag{29}$$

$$\omega = (-1)^p \cos^{-1}\left\{\frac{\bar{x}(r_o \cdot N) + \bar{y}(r_o \times k \cdot N)}{r_o^{\,2}}\right\} \tag{30}$$

where

$$p = \left\{\frac{1 - \operatorname{sgn}\left[\bar{x}z_o' + \bar{y}(x_o'k_2 - y_o'k_1)\right]}{2}\right\} ,$$

$$\Omega = (-1)^q \cos^{-1} N_1 , \tag{31}$$

where
$$q = \left\{\frac{1 - \operatorname{sgn} N_2}{2}\right\} .$$

Having obtained values for a, e, σ, i, Ω, and ω, g_{ij} may be evaluated for each time of observation. The first step in the computing procedure consists of solving for the eccentric anomaly E_j in Kepler's equation,

$$E_j - e \sin E_j = nt_j + \sigma \ . \tag{32}$$

The position of the satellite as a function of time is determined in the x"y"z"-coordinate system.

$$f_j = 2 \tan^{-1}\left[\sqrt{\frac{1 + e}{1 - e}} \tan\left(\frac{E_j}{2}\right)\right] ; \tag{33}$$

$$r_j = a(1 - e \cos E_j) \ ; \tag{34}$$

$$x''_j = r_j \cos f_j \ ; \tag{35}$$

$$y''_j = r_j \sin f_j \ . \tag{36}$$

z''_j is zero according to the definition of the x"y"z"-coordinate system. A transformation to the x'y'z' coordinates can be achieved by three rotations as follows:

$$\begin{pmatrix} x'_j \\ y'_j \\ z'_j \end{pmatrix} = R_3(-\Omega)R_1(-i)R_3(-\omega) \begin{pmatrix} x''_j \\ y''_j \\ 0 \end{pmatrix} . \tag{37}$$

Finally the position in the xyz-coordinate system may be obtained by two additional rotations and a translation.

$$\begin{pmatrix} x_j \\ y_j \\ z_j \end{pmatrix} = R_2(90^\circ - \phi)R_3(\theta_j) \begin{pmatrix} x'_j \\ y'_j \\ z'_j \end{pmatrix} - \begin{pmatrix} \rho_\phi \sin \Delta \\ 0 \\ \rho_\phi \cos \Delta \end{pmatrix} . \tag{38}$$

Referring to (1), g_{ij} may be then expressed in terms of the satellite's positions at time t_j and t_{j+1} .

$$g_{ij} \equiv \sqrt{x_{j+1}^2 + y_{j+1}^2 + z_{j+1}^2} + \sqrt{(x_{j+1} - x_i)^2 + (y_{j+1} - y_i)^2 + (z_{j+1} - z_i)^2} - \sqrt{x_j^2 + y_j^2 + z_j^2} - \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2} \, , \qquad (39)$$

where (x_i, y_i, z_i) is the surveyed position of the ith receiver. Finally, the residuals Δv_{ij} may be determined from

$$\Delta v_{ij} = v_{ij} - g_{ij} \quad . \qquad (40)$$

Having evaluated the vector ΔV, there remains the problem of determining the Jacobian J. The necessary differentiation may be carried out numerically, but the computing time will be reduced and the accuracy increased if the derivatives are evaluated from analytical expressions. Recalling that for all values of i and j,

$$J \equiv J\left(\frac{g_{10}, \; . \; . \; . \; , g_{ij}, \; . \; . \; .}{x_o, \, y_o, \, z_o, \, \dot{x}_o, \, \dot{y}_o, \, \dot{z}_o}\right) ,$$

let

$$J = J_1 J_2 J_3 J_4 \; ,$$

where

$$J_1 \equiv \left(\frac{g_{10}, \; . \; . \; . \; , g_{ij}, \; . \; . \; .}{x_{j+1}, \, y_{j+1}, \, z_{j+1}, \, x_j, \, y_j, \, z_j}\right) , \qquad (41)$$

$$J_2 \equiv \left(\frac{x_{j+1}, \, y_{j+1}, \, z_{j+1}, \, x_j, \, y_j, \, z_j}{a, \, e, \, \sigma, \, \omega, \, \Omega, \, i}\right) , \qquad (42)$$

$$J_3 \equiv \left(\frac{a, \, e, \, \sigma, \, \omega, \, \Omega, \, i}{x_o', \, y_o', \, z_o', \, \dot{x}_o', \, \dot{y}_o', \, \dot{z}_o'}\right) , \qquad (43)$$

$$J_4 \equiv \left(\frac{x_o', \, y_o', \, z_o', \, \dot{x}_o', \, \dot{y}_o', \, \dot{z}_o'}{x_o, \, y_o, \, z_o, \, \dot{x}_o, \, \dot{y}_o, \, \dot{z}_o}\right) . \qquad (44)$$

The orders of the above matrices are $(i \cdot j \times 6)$ for J_1, and (6×6) for J_2, J_3 and J_4. A distinct advantage of this method of evaluating J results from the fact that the function g_{ij} appears only in J_1. Hence, if the solution is applied to other types of measurements, only J_1 needs revision for the appropriate evaluation of J. This is trivial compared to the effort required to derive the derivatives contained in J_2 and J_3. The expressions for many of the elements of these Jacobian matrices are rather long and involved, and therefore will not be presented here, but the complete results are reported elsewhere.[5]

D. Initial Approximations for the Single-Pass Solution

Convergence of the single-pass computation rests primarily upon the adequacy of the initial approximations for position and velocity. It has been established that, for a system consisting of a single receiver and an earth-bound transmitter at opposite ends of a 400 mile base line, convergence is assured when the error in each coordinate of the initial estimate is not in excess of 50 to 75 miles and the velocity components are correct to within 1/2 to 1 mile per second. However, if single pass measurements are available from two or more receivers, the system geometry is greatly strengthened. Convergence can then be expected when the initial approximations are within 150 to 200 miles of the correct value in each coordinate and 1 to 2 miles per second in each velocity component. Larger errors may occasionally be tolerated, but the figures presented are intended to specify limits within which convergence may be reasonably assured.

Therefore, it has been necessary to develop a supporting computation to provide relatively accurate initial approximations to position and velocity for the primary computation. Several successful methods have been developed for this phase of the problem; but discussion will be confined to a few applications of a differential equation which approximately relates the motion of the satellite to the tracking observations. The following definitions will be useful in the derivation of this equation.

$R_T \equiv$ the radius vector from the Earth's center to the transmitting site.

$r_j \equiv$ the radius vector from the Earth's center to the position of the satellite at time t_j.

$\beta_j \equiv$ the angle between R_T and r_j.

$(x''_T, y''_T, z''_T) \equiv$ the position of the transmitting site.

$(x''_j, y''_j, 0) \equiv$ the position of the satellite at time t_j.

$\rho_j \equiv$ the distance from the transmitting site to the satellite at time t_j.

$\rho_{ij} \equiv$ the distance from the ith receiver to the satellite at time t_j.

$H \equiv$ the altitude of the satellite above the Earth's surface.

$v \equiv$ the velocity of the satellite.

To simplify the problem, certain assumptions have been made:

1. the satellite moves in a circular Keplerian orbit,
2. β_j is relatively small throughout the period of observation,
3. the Earth is not rotating.

A number of useful relationships may be derived as a result of these assumptions.

$$|r_j| = r = R + H ,$$

where H is constant.

$$v = nr = \sqrt{(\dot{x}''_j)^2 + (\dot{y}''_j)^2} .$$

$$\left(\frac{R}{R+H}\right) = \left(\frac{Rv^2}{\mu}\right).$$

$$\ddot{x}''_j = -n^2 x''_j \; ; \; \ddot{y}''_j = -n^2 y''_j .$$

$$\cos \beta_j \cong 1 .$$

$$R_T = \text{constant} .$$

The reference frame for this derivation is the x"y"z"-coordinate system which has been defined previously. It follows from the definition of ρ_j that

$$\rho_j = \sqrt{(x''_j - x''_T)^2 + (y''_j - y''_T)^2 + (z''_T)^2} . \tag{45}$$

Differentiating twice with respect to time yields

$$\dot{\rho}_j^{\,2} + \rho_j\ddot{\rho}_j = (\dot{x}''_j)^2 + (\dot{y}''_j)^2 + \ddot{x}''_j(x''_j - x''_T) + \ddot{y}''_j(y''_j - y''_T) , \tag{46}$$

which may be simplified to

$$\begin{aligned} \dot{\rho}_j^{\,2} + \rho_j\ddot{\rho}_j &= v^2 - n^2(r^2 - x''_j x''_T - y''_j y''_T) , \\ &= n^2(R_T \cdot r_j) , \\ &= n^2 r\, R \cos\beta , \\ &= v^2 \left(\frac{R}{R + H}\right) \cos\beta , \\ &= \frac{Rv^4}{\mu} \cos\beta , \\ &\approx \frac{Rv^4}{\mu} . \end{aligned}$$

It follows that

$$\ddot{\rho}_j \approx \frac{\frac{Rv^4}{\mu} - \dot{\rho}_j^{\,2}}{\rho_j} . \tag{47}$$

A similar expression may be derived for ρ_{1j}. Recalling the definition for g_{1j}, we conclude that

$$\ddot{g}_{1j} \approx \frac{A - \dot{\rho}_j^{\,2}}{\rho_j} + \frac{A - \dot{\rho}_{1j}^{\,2}}{\rho_{1j}} , \tag{48}$$

where

$$A = \frac{Rv^4}{\mu} .$$

Let us define a right-hand rectangular coordinate system, as shown in Figure 61, with the origin at the transmitter and the z-axis positive in the direction of the vertical. The y-axis is formed by the intersection of the tangent plane at the transmitter with the plane determined by the transmitter, the ith receiver, and the Earth's center. The receiver will then be at the known point $(0, y_i, z_i)$. If the variable point (x_j, y_j, z_j) indicates the position of the satellite, the slant ranges from the transmitter and the ith receiver are respectively given by

$$\rho_j = \sqrt{x_j^2 + y_j^2 + z_j^2} \ , \tag{49}$$

$$\rho_{ij} = \sqrt{x_j^2 + (y_j - y_i)^2 + (z_j - z_i)^2} \ , \tag{50}$$

from which it follows that

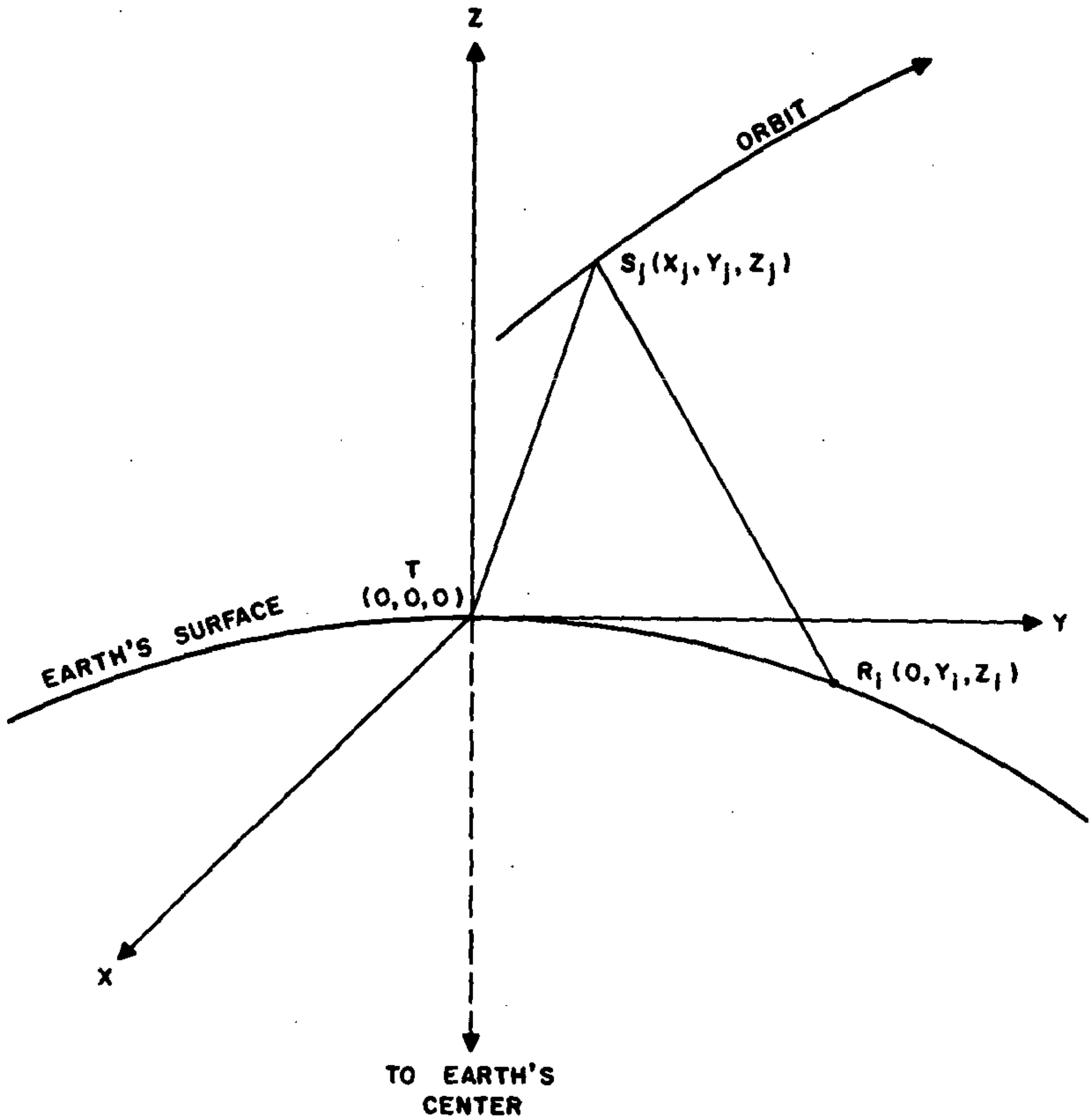
$$\dot{\rho}_j = \frac{x_j\dot{x}_j + y_j\dot{y}_j + z_j\dot{z}_j}{\rho_j} \ , \tag{51}$$

$$\rho_{ij} = \frac{x_j\dot{x}_j + (y_j - y_i)\dot{y}_j + (z_j - z_i)\dot{z}_j}{\rho_{ij}} \ . \tag{52}$$

In the three-beam mode of operation, the satellite will be approximately in the yz-plane at t_o, which is defined as the time halfway between the initiation and termination of tracking in the center beam. Let the satellite's position and velocity at this time be defined as (x_o, y_o, z_o) and $(\dot{x}_o, \dot{y}_o, \dot{z}_o)$, respectively. Obviously, x_o may be approximated by zero and we may safely assume that the vertical component of velocity is small and can well be approximated by zero. The last pair of equations then reduce to

$$\dot{\rho}_o = \frac{y_o\dot{y}_o}{\sqrt{y_o^2 + z_o^2}} \ , \tag{53}$$

$$\dot{\rho}_{io} = \frac{(y_o - y_i)\dot{y}_o}{\sqrt{(y_o - y_i)^2 + (z_o - z_i)^2}} \ . \tag{54}$$



GEOMETRY FOR DETERMINING
THE INITIAL APPROXIMATIONS

Figure 61

Let f_{io} and $\dot{f}_{io}$ be the Doppler frequency and rate of change of frequency for the ith receiver at t_o. It follows that

$$f_{io} = \frac{1}{\lambda} (\dot{\rho}_o + \dot{\rho}_{io}) . \tag{55}$$

From equation (48), we conclude

$$\dot{f}_{io} = \frac{A - (\dot{\rho}_o)^2}{\lambda \rho_o} + \frac{A - (\dot{\rho}_{io})^2}{\lambda \rho_{io}} . \tag{56}$$

Expressing equations (55) and (56) in terms of the position coordinates and velocity components of the satellite at time, t_o, yields

$$f_{io} = \frac{\dot{y}_o}{\lambda} \left[\frac{y_o}{\sqrt{y_o^2 + z_o^2}} + \frac{(y_o - y_i)}{\sqrt{(y_o - y_i)^2 + (z_o - z_i)^2}} \right] . \tag{57}$$

$$\dot{f}_{io} = \frac{A - \left[\dfrac{y_o \dot{y}_o}{\lambda \sqrt{y_o^2 + z_o^2}} \right]^2}{\lambda \sqrt{y_o^2 + z_o^2}} + \frac{A - \left[\dfrac{(y_o - y_i) \dot{y}_o}{\lambda \sqrt{(y_o - y_i)^2 + (z_o - z_i)^2}} \right]^2}{\lambda \sqrt{(y_o - y_i)^2 + (z_o - z_i)^2}} \tag{58}$$

Let us assume a specific orbital inclination. With our previous assumption of circular motion, $\dot{y}_o$ may readily be computed as a function of y_o and z_o. Then equations (57) and (58) will likewise provide f_{io} and $\dot{f}_{io}$ as functions of position in the yz-plane. Thus, for a given inclination, families of curves may be computed and plotted in the yz-plane for both f_{io} and $\dot{f}_{io}$. Figure 62 presents such a plot, for an inclination of 80^o, with the transmitter and receiver separated by 434 miles and with both located 35^o off the equator. To attain symmetry and simplify the construction of such charts, z_i was assumed to be zero, which is a reasonable approximation for this approach to the problem. If similar charts are prepared for a number of inclinations, satisfactory initial approximations may be rather quickly and easily obtained by the following operations:

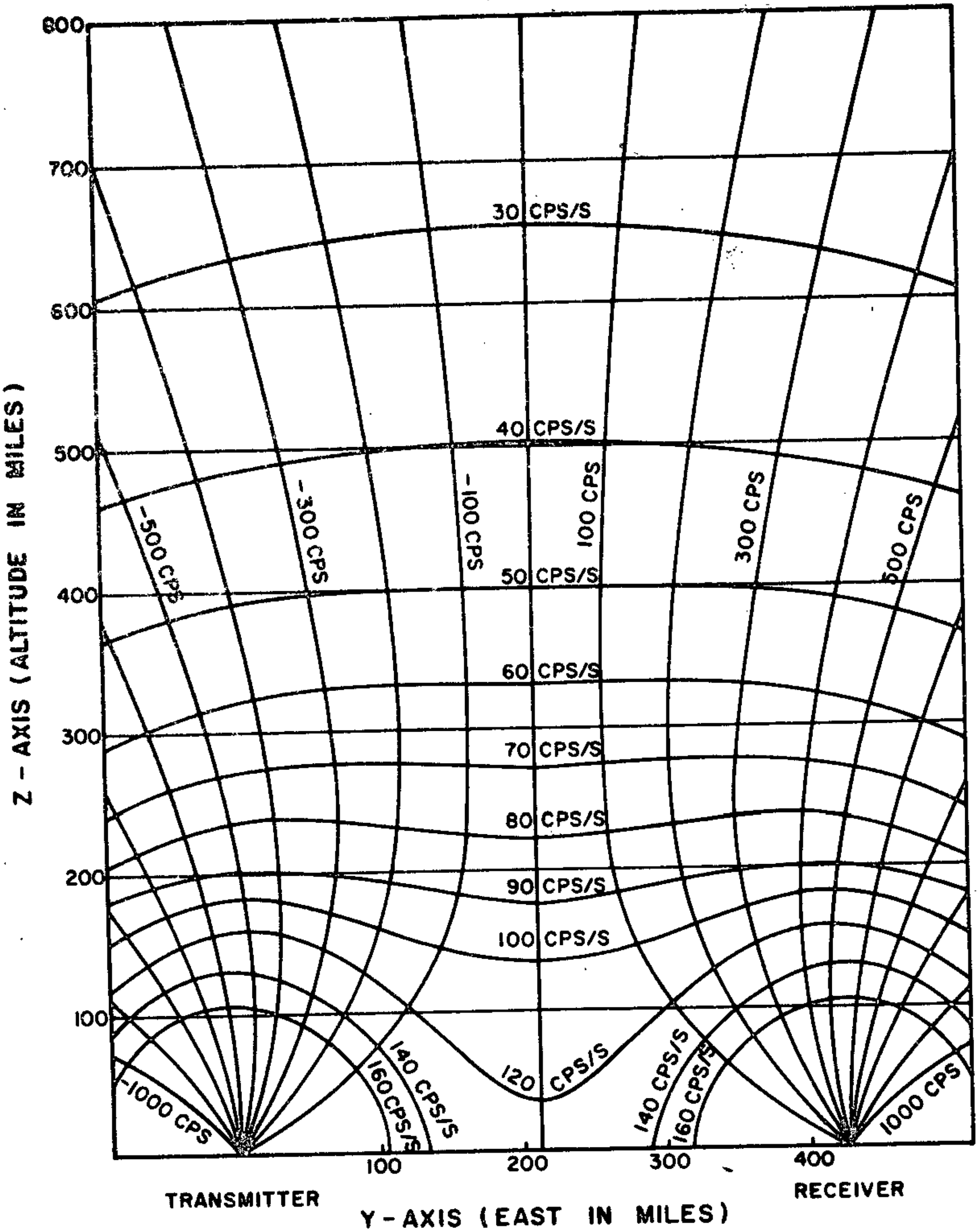
1. Assume an inclination. This, of course, is equivalent to selecting a chart. Accuracy is not essential at this stage since the estimate may be in error by 15° or more without preventing convergence.

2. Enter the chart with the observed values of f_{1o} and $\dot{f}_{1o}$ to determine an appropriate position within the yz-plane.

3. Approximate the velocity components. These should be consistent with the assumption of circular motion, the height determined in step 2, and the assumed inclination.

4. Determine the position and velocity components in the coordinate system for the primary solution by an appropriate coordinate transformation.

In addition to the graphical method, a digital solution has been devised for eqs. (57) and (58). As in the previous development, we have two measurements available and desire to determine three unknowns. In this approach, one unknown is determined by establishing an upper bound and assuming a value which is a fixed distance from this bound. The distance has been selected to place the variable between its upper and lower bounds in a position which is favorable for convergence of the primary computation. In this method, we chose to start by approximating z_o. It may be observed in Fig. 62 that, for larger values of $\dot{f}_{1o}$, the maximum value of z_o occurs above either the transmitter or receiver while, for smaller values of $\dot{f}_{1o}$, the maximum value of z_o occurs over the mid-point of the base line. The first step in the computation is to determine a maximum value for z_o. To this end, $\dot{y}_o$ is eliminated from eqs. (57) and (58) to yield an expression which varies only in y_o and z_o. A appears in this expression, but it is also a function of these variables. The resulting equation may be solved by numerical methods for z_o with $y_o = 0$ and then, solved a second time for z_o with $y_o = (1/2)y_j$. The larger of these results is to be used as a value for $(z_o)_M$ which is defined to be the maximum possible value of z_o. Assuming the altitudes of all satellites to be in excess of 75 miles, we may conclude, from the general characteristics of the family of curves for $\dot{f}_{1o}$ in Fig. 62, that the



DOPLOC FREQUENCY AND RATE OF CHANGE OF FREQUENCY AS A FUNCTION OF POSITION IN THE YZ - PLANE (FOR 80° INCLINATION)

Figure 62

satellite's altitude will differ from $(z_o)_M$ by no more than 100 miles. Since an error of 50 miles may be tolerated in the approximation for each coordinate, $\left[(z_o)_M - 50\right]$ is a suitable value for z_o. With the altitude thus determined, we may solve eqs. (57) and (58) for y_o and $\dot{y}_o$. In the process, A and hence the velocity, will be determined. With $\dot{z}_o$ assumed as zero, $\dot{x}_o$ may be readily evaluated to complete the initial approximations which consist of the position $(0, y_o, z_o)$ and the velocity $(\dot{x}_o, \dot{y}_o, 0)$. It is worth noting that there are a pair of solutions for y_o and $\dot{y}_o$. Further, the method does not determine the sign of $\dot{x}_o$. If, in addition, we accept the possibility of negative altitudes for the mathematical model at least, we arrive at eight possible sets of initial conditions which are approximately symmetrical with respect to the base line and its vertical bisector. It is an interesting fact that all eight, when used as input for the primary computation, lead to convergent solutions which exhibit the same type of symmetry as the approximations themselves. Of course, it is trivial to eliminate the four false solutions which place the orbit underground. Further, two additional solutions may be eliminated by noting that the order in which the satellite passes through the three antenna beams determines the sign of $\dot{x}_o$. In the two remaining possibilities, $\dot{y}_o$ is observed to have opposite signs. Since the y-axis of the DOPLOC system has been oriented from west to east, the final ambiguity may be resolved by assuming an eastward component of velocity for the satellite - certainly a valid assumption to date. In any event, all ambiguity may be removed from the solution by the addition of one other receiver. Moreover, this would significantly improve the geometry of the system and thereby strengthen the solution.

These two methods, for obtaining initial approximations, have been developed for a system which provides observations of the type displayed in Fig. 58(b). If (very) minor modifications are made in the procedures, both methods may readily be applied to data of the type presented in Fig. 58(c).

Indeed, with any tracking system that provides observations of satellite velocity components, eq. (48) furnishes an adequate base for establishing an approximate orbit to serve as an initial solution which may be refined by more sophisticated methods.

E. Multiple-Pass Solution

Single-pass orbit determination is unquestionably a primary requirement for any satellite detection system. Of no less importance is the capability of the system to generate sufficient accuracy in the computed orbit to permit positive identification and predictions which are adequate for later acquisition. Improved accuracy is most readily obtained by increasing the number of observations and lengthening the time interval over which data are collected. Both of these objectives may be realized by simultaneously using data from several passes in an orbital determination. Further improvement will result if the system may be expanded to include additional receivers. The single-pass solution has already been programmed to accommodate several receivers; but it is inadequate for a solution with input data from more than one pass. Therefore, a separate solution for dealing specifically with this phase of the problem has been under development for sometime. The derivation of the computing procedure is essentially complete; and in fact, a few encouraging results have already been obtained. However, the method still requires the introduction of a few minor refinements as well as extensive testing to verify its compatibility with a wide range of input data.

The multiple-pass solution was designed to allow a major portion of the computing procedure for the single-pass method to be used in the actual computation. It is assumed that the satellite moves in an unperturbed, or Keplerian, orbit for those short intervals of time that it is under observation by the DOPLOC System. Otherwise, the satellite is considered to move in a perturbed orbit. The latter is determined by thirteen parameters from which six time-varying Keplerian orbital parameters may be readily derived. For a given period of observation, the Keplerian parameters are determined for t_o, a fixed time within the tracking interval. These

parameters are then assumed to determine the orbit for the few minutes that the satellite remains within the volume coverage of the DOPLOC System. Thus, if data are available for Q revolutions, Q sets of Keplerian orbital parameters, each constant within a given interval of observation, will be expressed in terms of the thirteen unknowns. The latter may then be adjusted by a series of differential corrections to obtain a least-squares fit to all observations for two or more revolutions. No attempt has been made to determine particular perturbing elements such as drag. Rather, it has been assumed that an empirical determination of the thirteen unknowns will adequately reflect the total effect of all perturbations upon the orbit. To conserve computing time, it is considered desirable to use input that consists of the integrated Doppler frequencies over time intervals of several seconds as recommended for the single-pass solution.

Let the subscripts i and j be defined as before. A third subscript, q, will be introduced to specify the satellite revolution number. The perturbed orbital parameters are expressed in terms of α_h where h ranges from one through thirteen. For the qth revolution, we define the unperturbed parameters as follows:

$$i_q \equiv \alpha_1 , \tag{59}$$

$$\Omega_q \equiv \alpha_2 + \alpha_3 (t_{oq} - t_{oq_o}) + \alpha_4 (t_{oq} - t_{oq_o})^2 , \tag{60}$$

$$\omega_q \equiv \alpha_5 + \alpha_6 (t_{oq} - t_{oq_o}) + \alpha_7 (t_{oq} - t_{oq_o})^2 , \tag{61}$$

$$t_{oq} \equiv t_{oq_o} + \alpha_8 (q-q_o+\Delta\gamma_q) + \alpha_9 (q-q_o+\Delta\gamma_q)^2 + \alpha_{10} (q-q_o+\Delta\gamma_q)^3 , \tag{62}$$

$$e_q \equiv \alpha_{11} + \alpha_{12} (q-q_o+\Delta\gamma_q) + \alpha_{13} (q-q_o+\Delta\gamma_q)^2 , \tag{63}$$

where

$q_o \equiv$ the minimum value of q ,

$t_{oq} \equiv$ the time for which the unperturbed parameters are computed for the qth revolution,

$\Delta\gamma_q \equiv \gamma_q - \gamma_{qo}$,

$\gamma_q \equiv$ the angular distance along the orbit from the equator to the satellite at time t_{oq} .

From eq. (62), we conclude that

$$a_q = \sqrt[3]{\frac{\mu}{4(\pi)^2}} \left[\alpha_8 + 2\alpha_9 (q-q_o+\Delta\gamma_q) + 3\alpha_{10} (q-q_o+\Delta\gamma_q)^2\right]^{2/3} \quad (64)$$

The set of unperturbed parameters for qth revolution is completed with the computation of σ_q from the equations

$$E_q = 2\tan^{-1}\left[\sqrt{\frac{1 - e_q}{1 + e_q}} \tan\left(\frac{\gamma_q - \omega_q}{2}\right)\right] , \quad (65)$$

$$\sigma_q = E_q - e_q \sin E_q . \quad (66)$$

γ_q may be evaluated with sufficient accuracy from the single-pass solution for position at the time, t_{oq}. i_q, Ω_q, ω_q, e_q, a_q and σ_q constitute a set of unperturbed parameters for each revolution q for which tracking observations are available. Further, they are functionally related to α_h. Hence, the observed data may be expressed as a function of the set of parameters α_h.

As in the single-pass method, the solution is obtained by using least-squares methods to compute a series of differential corrections to initial approximations for the set of parameters, α_h. For each value of q, eqs. (32) through (40) may be used as before to compute the residuals, ΔV_{ijq}. The least-squares solution is obtained from the matrix equation

$$\Delta\alpha = (\bar{J}^*\bar{J})^{-1} \bar{J}^* \Delta V , \quad (67)$$

where ΔV and $\Delta\alpha$ are column matrices whose elements are respectively the residuals and the differential corrections for the set of unknowns α_h. $\bar{J}$ is a Jacobian defined as follows:

$$\bar{J} \equiv \begin{pmatrix} \bar{J}_{q_o} \\ \vdots \\ \bar{J}_q \\ \vdots \end{pmatrix},$$

where

$$\bar{J}_q \equiv \left(\frac{g_{10q}, \ldots\ldots, g_{ijq}, \ldots\ldots}{\alpha_1, \alpha_2, \ldots\ldots\ldots\ldots, \alpha_{13}}\right). \quad (68)$$

The definition for g_{ijq} is similar to that for g_{ij} of the single-pass solution. Let

$$\bar{J}_q = J_{1q} \, J_{2q} \, J_q \,,$$

where

$$J_{1q} \equiv \left(\frac{g_{10q}, \; \cdot \; \cdot \; \cdot \; \cdot \; \cdot \; g_{ijq}, \; \cdot \; \cdot \; \cdot \; \cdot \; \cdot \; \cdot \; \cdot \; \cdot}{x_{(j+1)q}, \; y_{(j+1)q}, \; z_{(j+1)q}, \; x_{jq}, \; y_{jq}, \; z_{jq}} \right) , \quad (69)$$

$$J_{2q} \equiv \left(\frac{x_{(j+1)q}, \; y_{(j+1)q}, \; z_{(j+1)q}, \; x_{jq}, \; y_{jq}, \; z_{jq}}{a_q, \; e_q, \; \sigma_q, \; \omega_q, \; \Omega_q, \; i_q} \right) , \quad (70)$$

$$J_q \equiv \left(\frac{a_q, \; e_q, \; \sigma_q, \; \omega_q, \; \Omega_q, \; i_q}{\alpha_1, \; \alpha_2, \; \cdot \; \cdot \; \cdot \; \cdot \; \cdot \; \cdot \; \alpha_{13}} \right) . \quad (71)$$

It will be noted that J_{1q} and J_{2q} have definitions which are similar to J_1 and J_2 of the single-pass solution. Hence, the analytical expressions for the elements of these matrices are identical to those for J_1 and J_2 which have been reported upon previously[2]. The elements of J_q have not been published but are easily derived, and therefore, will not be presented.

To summarize, initial approximations for α_h are derived from the single-pass solutions for each value of q. We assume the perturbed parameters a_q, e_q, σ_q, ω_q, Ω_q and i_q can be adequately expressed in terms of α_h by eq. (59) through (63). Further, it is assumed that they remain constant during each short period of observation, but otherwise vary in accordance with this same set of equations. Hence, we have sets of Keplerian parameters for each period of observation. They are used to compute the elements of the ΔV matrix for the least-squares solution to determine appropriate differential corrections for the estimated values of α_h. The process is iterated until convergence is achieved. The resulting set of α_h provide perturbed orbital parameters as a function of time and revolution number. The results may also be used to predict the time and position of future passes of the satellite as an aid in later acquisition.

F. Computational Results

Numerous convergent solutions have been obtained with both simulated and actual field data serving as computer input. Since the latter are of major interest, the discussion will be restricted to results obtained from real data. The present results were obtained from observations which were recorded during a period when the WSMR receiver was inoperable and, therefore, are derived from data recorded by a single receiver. Included with the DOPLOC results are orbital parameters which were determined and published by the National Space Surveillance Control Center (Space Track). As an aid in comparing the two sets of determinations, the Space Track parameters have been converted to the epoch times of the DOPLOC reductions.

The initial successful reduction for the Fort Sill, Forrest City system was achieved for Revolution 9937 of Sputnik III. The DOPLOC observations, as well as the results, are presented in Fig. 63. Measurements were recorded for 28 seconds in the south antenna beam, 7 seconds in the center beam, and 12 seconds in the north beam with two gaps in the data of 75 seconds each. Thus, observations were recorded for a total of 47 seconds within a time interval of 3 minutes and 17 seconds. Using the graphical method described in the previous section to obtain initial approximations, convergence was achieved in three iterations, on the first pass through the computing machine. In comparing the DOPLOC and Space Track solutions, it will be noted that there is reasonably good agreement in the values for a, e, i, and Ω, particularly for the latter two. This is characteristic of the single-pass solution when the eccentricity is small and the computational input is limited to Doppler frequency. Since the orbit is almost circular, σ and ω are less significant than the other parameters and likewise, are more difficult for either system to determine accurately. However, as a result of the small eccentricity, the sum of ω and σ is a rather good approximation to the angular distance along the orbit from the nodal point to the position of the satellite at epoch time and as such, provides a basis of comparison between the two systems. In the DOPLOC solution, $(\omega + \sigma) = 32.66^{\circ}$ while the Space Track determination yields a value of 35.73°,

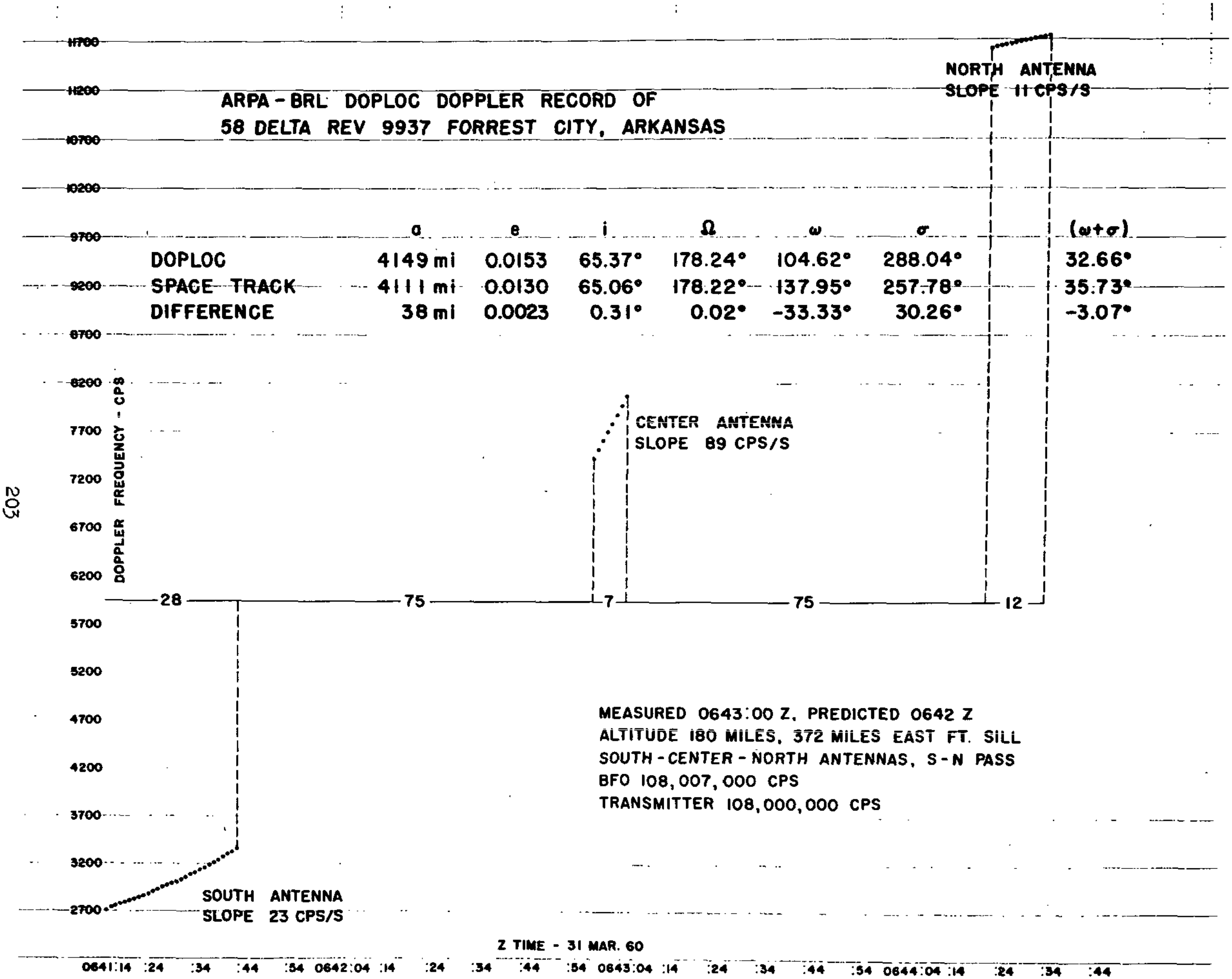

ARPA - BRL DOPLOC DOPPLER RECORD OF
58 DELTA REV 9937 FORREST CITY, ARKANSAS
a e i Ω ω σ (ω+σ)
DOPLOC 4149 mi 0.0153 65.37° 178.24° 104.62° 288.04° 32.66°
SPACE TRACK 4111 mi 0.0130 65.06° 178.22° 137.95° 257.78° 35.73°
DIFFERENCE 38 mi 0.0023 0.31° 0.02° -33.33° 30.26° -3.07°
NORTH ANTENNA
SLOPE 11 CPS/S
CENTER ANTENNA
SLOPE 89 CPS/S
SOUTH ANTENNA
SLOPE 23 CPS/S
28
75
7
75
12
MEASURED 0643:00 Z, PREDICTED 0642 Z
ALTITUDE 180 MILES, 372 MILES EAST FT. SILL
SOUTH - CENTER - NORTH ANTENNAS, S - N PASS
BFO 108,007,000 CPS
TRANSMITTER 108,000,000 CPS
DOPPLER FREQUENCY - CPS
11700
11200
10700
10200
9700
9200
8700
8200
7700
7200
6700
6200
5700
5200
4700
4200
3700
3200
2700
Z TIME - 31 MAR. 60
0641:14 :24 :34 :44 :54 0642:04 :14 :24 :34 :44 :54 0643:04 :14 :24 :34 :44 :54 0644:04 :14 :24 :34 :44

Figure 63

a difference of 3.07° between the two sets of results. To summarize, when limited to single-pass, single-receiver observations, the DOPLOC system provides an excellent determination of the orientation of the orbital plane, a good determination of the shape of the orbit, and a fair-to-poor determination of the orientation of the ellipse within the orbital plane.

Occasionally, excellent results have been obtained for both σ and ω; but in general, the interim DOPLOC system with its present limitations fails to provide consistently good single-pass evaluations of these two quantities. Therefore, in presenting the remaining single-pass DOPLOC reductions, σ and ω have been eliminated from further consideration. Results have been indicated in Table I for six revolutions of Discoverer XI, including number 172 which was the last known revolution of this satellite. As a matter of interest, the position determined by the interim DOPLOC system for this pass indicated an altitude of 82 miles as the satellite crossed the base line 55 miles west of Forrest City. To provide a basis for evaluation of the DOPLOC results, orbital parameters, obtained by converting Space Track determinations to the appropriate epoch times, have been included in the table. Table I also contains a listing of the amount of data available for each reduction in addition to the total time interval within which the observations were collected. The observations recorded for the Fort Sill, Forrest City complex are plotted in Fig. 64 for the six revolutions of Discoverer XI which are summarized in Table I. In Fig. 65, results are tabulated for a reduction based on only seven frequency observations from a single pass over the interim DOPLOC system. These have been extracted from the complete set of observations previously presented for Sputnik III. They were selected to serve as a crude example of the type of reduction required for the proposed DOPLOC scanning-beam system. The example shows that the method is quite feasible for use with periodic, discrete measurements of frequency. Of course, the proposed system would normally yield several more observations than were available in the example.

There has not been sufficient time thus far to completely evaluate the computing methods for the multiple-pass solution. However, one set of results has been obtained for observations from revolutions 124, 140 and

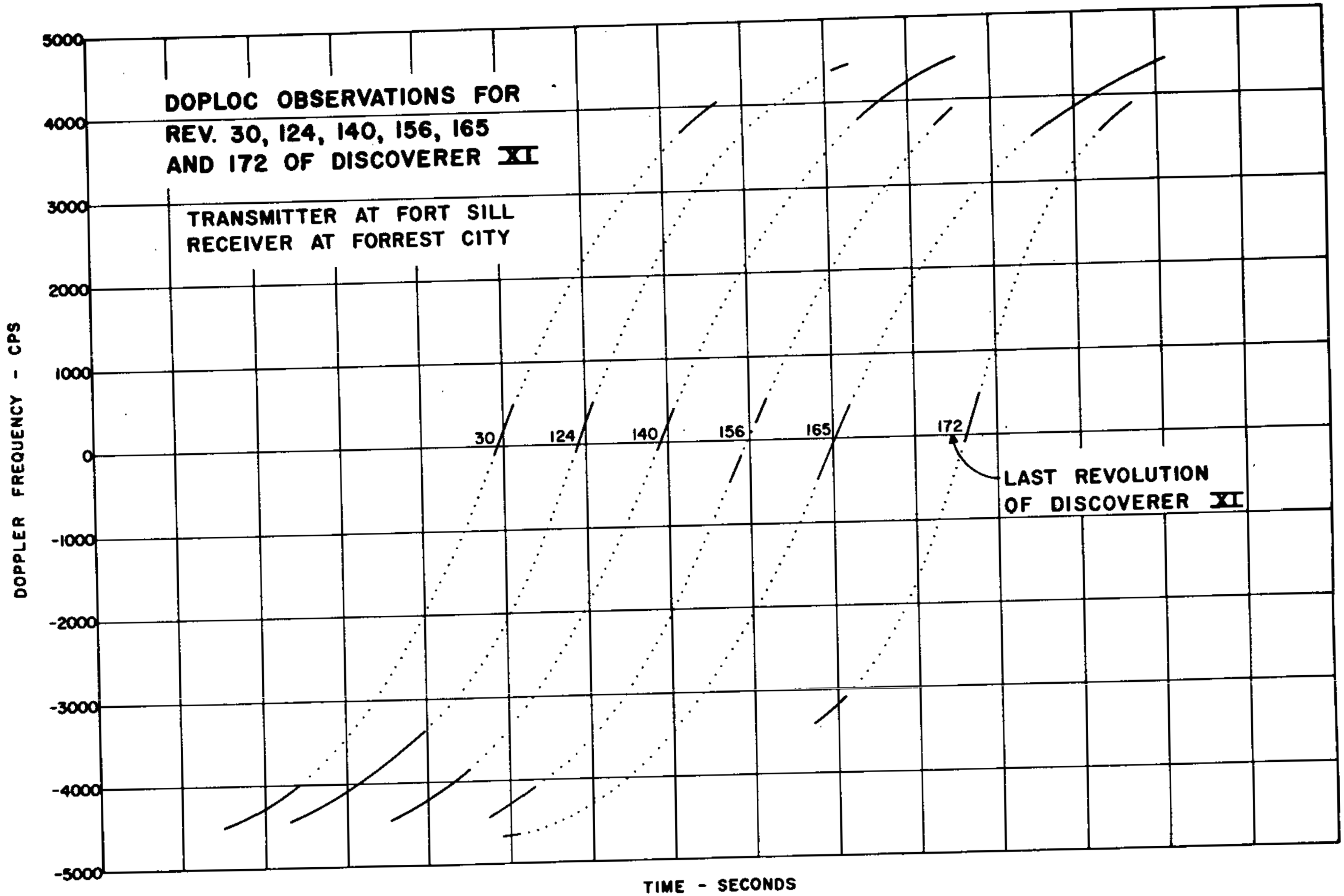

DOPLOC OBSERVATIONS FOR
REV. 30, 124, 140, 156, 165
AND 172 OF DISCOVERER XI
TRANSMITTER AT FORT SILL
RECEIVER AT FORREST CITY
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
DOPPLER FREQUENCY - CPS
30
124
140
156
165
172
LAST REVOLUTION
OF DISCOVERER XI
TIME - SECONDS

Figure 64

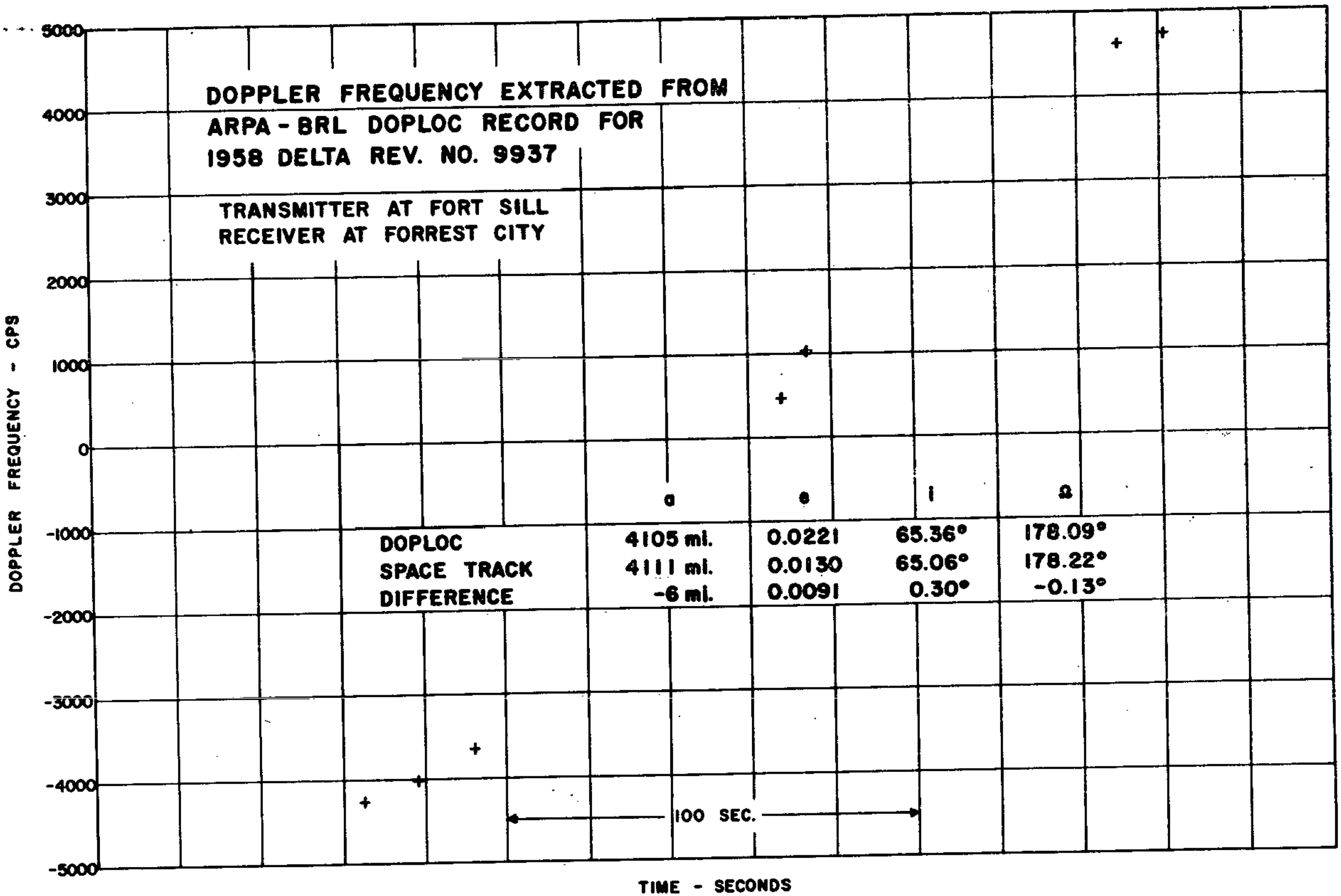

DOPPLER FREQUENCY EXTRACTED FROM
ARPA - BRL DOPLOC RECORD FOR
1958 DELTA REV. NO. 9937
TRANSMITTER AT FORT SILL
RECEIVER AT FORREST CITY
a
e
i
Ω
DOPLOC
4105 mi.
0.0221
65.36°
178.09°
SPACE TRACK
4111 mi.
0.0130
65.06°
178.22°
DIFFERENCE
-6 mi.
0.0091
0.30°
-0.13°
100 SEC.
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
DOPPLER FREQUENCY - CPS
TIME - SECONDS

Figure 65

TABLE I

Comparison of Single-pass DOPLOC and Space Track Results for Discoverer XI

	Revolution Number	a (miles)	e	i (degrees)	Ω (degrees)	Total Amount of Data (seconds)	Interval of Observation (seconds)
DOPLOC	30	4186	0.0295	80.15	215.92	35	123
Space Track		4189	0.0291	80.01	215.84		
Difference		- 3	0.0004	0.14	0.08		
DOPLOC	124	4115	0.0198	80.31	207.50	44	138
Space Track		4135	0.0203	80.10	207.27		
Difference		- 20	-0.0005	0.21	0.23		
DOPLOC	140	4138	0.0198	80.44	205.22	55	141
Space Track		4121	0.0178	80.10	205.78		
Difference		17	0.0020	0.34	- 0.56		
DOPLOC	156	4143	0.0300	80.79	204.50	25	117
Space Track		4108	0.0148	80.10	204.30		
Difference		35	0.0152	0.69	0.20		
DOPLOC	165	4037	0.0111	79.99	203.63	49	165
Space Track		4099	0.0128	80.10	203.50		
Difference		- 62	-0.0017	-0.11	0.13		
DOPLOC	172	4093	0.0189	80.44	203.18	35	90
Space Track		4091	0.0111	80.10	202.84		
Difference		2	0.0078	0.34	0.34		

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156 of Discover XI. These are presented in Table II where, as before, a comparison is made with Space Track results for the same revolutions. Overall agreement is excellent, and in general, the differences between the two determinations are of the same magnitude as the error to be expected in either set of parameters. Disagreement is excessive only in σ, the mean anomaly at epoch. For this particular parameter, the major portion of the error must be in the Space Track results, for the DOPLOC reduction is designed to force the satellite's calculated position to lie in the narrow east-west vertical beam of the tracking system at the actual time of observation. The resulting error in the DOPLOC determination of satellite passage is certainly less than one second. Hence, the angular error in position is relatively insignificant.

As an indication of the feasibility of using the multiple-pass solution for prediction, the DOPLOC results in Table II were used to compute the times of satellite passage through the mid-point of the vertical beam for revolutions 165 and 172. These results were compared to the observed times. The predictions were found to be two minutes early for 165 and seven minutes early for 172. Since the latter was the final revolution for this satellite, these predictions covered a period in which drag was increasing rapidly and extrapolation was rather hazardous. These results are considered reasonable for this portion of the orbit and would certainly have been adequate as an aid in acquisition.

G. Conclusion

These methods of solution have been shown to be both practical and useful by numerous successful applications with real as well as simulated data. Although results have been presented for passive data only, the computing procedure has been altered slightly and applied to active data with considerable success. Computing times are reasonable since convergent solutions have required from 20 to 40 minutes on the ORDVAC with the coding in floating decimal, whereas more modern machines would perform the same computation in a fraction of a minute. These methods allow the determination of a relatively accurate set of orbital parameters with as little

TABLE II

Comparison of Space Track and Multiple-pass DOPLOC Results for Discoverer XI

	Revolution Number	a (miles)	e	i (degrees)	Ω (degrees)	σ (degrees)	ω (degrees)
DOPLOC	124	4143	0.0206	80.37	207.48	20.37	123.54
Space Track		4135	0.0203	80.10	207.27	13.57	125.22
Difference		8	0.0003	0.27	0.21	6.80	- 1.68
DOPLOC	140	4125	0.0172	80.37	206.04	24.52	119.63
Space Track		4121	0.0177	80.10	205.78	13.98	121.53
Difference		4	-0.0005	0.27	0.26	10.54	- 1.90
DOPLOC	156	4108	0.0139	80.37	204.54	28.29	115.73
Space Track		4108	0.0148	80.10	204.30	14.81	117.86
Difference		0	-0.0009	0.27	0.24	13.48	- 2.13

as 1.5 to 3 minutes of intermittent observations from a single receiver when the signal source is a ground-based transmitter. While multi-receiver systems provide numerous distinct advantages, it has been shown that it is possible to obtain, routinely, quite satisfactory results with observations from a single receiver. However, it should be noted that a system with two receivers will reduce error propagation in the computations to approximately one tenth of that to be expected from a single receiver system.

Extension of the computational methods to include multiple-pass solutions results in a well-rounded and complete computing program for satellite detection and identification. Not only are the orbital elements much better determined, but the increased accuracy is sufficient to permit adequate prediction for future acquisition.

It should be emphasized that solutions have been obtained for actual field data, and further that such solutions were completely independent of other measuring systems. Results from the latter were used only for comparison and did not enter any phase of the computations leading to these solutions.

In conclusion, the methods are quite general and need not be confined to either Doppler measurements or Keplerian orbits. It is merely necessary to modify J_1, J_{1q}, g_{ij} and g_{ijq} to allow these methods to be applied to observations from any satellite or ICBM tracking system.

VIII. POTENTIAL OF DOPLOC SYSTEM IN ANTI-SATELLITE DEFENSE

If it can be assumed that within a reasonable period of time the population of earth bound artificial satellites will reach the predicted number of 10,000, it can be assumed with equal certainty that any adequate system of satellite detection, tracking and orbit cataloguing equipment will utilize the Doppler principle and at least some of the DOPLOC techniques. DOPLOC was certainly the first and probably is still the only system to have demonstrated its ability to consistently compute orbits within minutes after first detection by a single station from single pass data. The performance capability of the DOPLOC system is equal to that of any other known system. Continuous wave bi-static Doppler Radar and narrow band reception techniques combine to provide a uniquely economical utilization of the physically limited power and receiver sensitivity. The DOPLOC system has its greatest potential as a surveillance system for cataloguing and identifying satellites. Its application as an anti-satellite or ICBM defense system is limited in its present form. Either as a surveillance system by itself, or as a member of a family of sensors, it offers a low cost dependable method of detecting and cataloguing satellites over an extremely large volume of space. With modifications to the scan configuration the system may have application to the ICBM and the anti-satellite defense problem. An early warning feature would need to be incorporated since DOPLOC is presently effective primarily after one pass over the sensor.

ACKNOWLEDGEMENT

The author wishes to acknowledge that most of the work done under the DOPLOC project (ARPA Order 8-58) was directed and supervised by Mr. L. G. de Bey, recently deceased. As indicated by the title, this report is intended to be a technical summary covering the entire project. The material presented was therefore compiled from various reports and sources and represents the work of most of the technical staff of the Electronic Measurements Branch of the Ballistic Measurement Laboratory over the period July 1958 - 30 June 1960. Section VII, "Satellite Orbit Determination from DOPLOC Data" was authored entirely by Mr. R. B. Patton, Jr. Others who made major contributions to the program were V. W. Richard, C. L. Adams, K. A. Richer, K. A. Pullen, Jr., R. E. A. Putnam, R. Vitek, H. Lootens, C. Shafer and K. Patterson. Material extracted from the work of contractors is referenced in the text.

Alfred H. Hodge

A. H. HODGE

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Department of the Army
Washington 25, D. C.

1 Commanding Officer
Diamond Ordnance Fuze Laboratories
ATTN: Technical Information Office
Branch 012
Washington 25, D. C.

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Armed Services Technical
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White Sands Annex - BRL
White Sands Missile Range
New Mexico

2 Commanding General
Army Ballistic Missile Agency
ATTN: Dr. C. A. Lundquist
Dr. F. A. Speer
Redstone Arsenal, Alabama

1 Director
Advanced Research Projects Agency
Department of Defense
Washington 25, D. C.

1 Director
National Aeronautics & Space
Administration
1520 H Street, N.W.
Washington 25, D. C.

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Satellites - Detection
Radar tracking - Satellites
Doppler tracking systems - Design

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